585

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An investigation into wetland soil-implement mechanics

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ABSTRACT

An investigation was initiated to obtain some understanding on the behaviour of soil at higher moisture content and to explore the potential of preparing paddy fields with reduced amounts of water. This investigation comprised of three separate studies.

Based on existing information that water could be reduced when soil clods were initially formed prior to flooding, the effects of clod size, clod initial moisture content and confining states on the rate of water uptake were explored. The moisture gradients within clods wetted and dried for different period of times were also studied. The results of the clod wetting experiments show that the rate of water uptake by capillarity was greatest when clods were initially very dry and smaller clods tended to absorb water faster than bigger clods when under confined conditions. Confining had no effect on infiltration when the initial condition was very wet. On drying, the smallest clod dried the fastest, reduced greater volume and increased its dry bulk density significantly. Larger clods required longer drying period to arrive at a uniform moisture profile within as compared to smaller clods. Results from the wetting experiments were tested against the infiltration model of Jarvis and Leeds-Harrison (1987) and a model developed based on linear flow of heat into a solid (Carslaw and Jaeger, 1959).

A second project involved the study of soil deformation at high moisture contents in an attempt to produce clods with minimum draught force using simple relieved tines at various rake angles and depths in a soil tank. The principal objective of the study was to utilise soil implement mechanics knowledge to improve the efficiency of soil preparation for wetland crops. Aspects like the nature of soil disturbance, extent of disturbance and draught requirement were investigated. The soil was in a plastic consistency prepared to three specified density states of 940, 1000 and 1250 kg/m^3. The soil disturbance pattern was monitored using implanted coloured beads and glass sided tank studies. In addition, the extent and height of heave and surface disturbance were noted.

Predictive models based upon Mohr-Coulomb soil mechanics theory were developed to predict the interaction between the soil and simple implements at three rake angles. These were based on the lateral failure theory of Godwin and Spoor (1977) and the two dimensional soil failure model of Hettiaratchi and Reece (1974). Results from the single tine study were tested against the models. A sliding resistance component and crescent effect were incorporated to improve the predictions for the 45° and 90° rake angle tines. The magnitude of each mode of failure is dependent upon the critical aspect ratio which varies with tine rake angles and soil conditions. The mode of failure is considered to be lateral when the tine aspect ratio is larger than the critical aspect ratio and an upward failure when the tine aspect ratio is lower than the critical aspect ratio. The predicted results are in close agreement with the results of the experimental studies. For the backward raked tine, a model was developed based on the formation of an elliptical wedge and bearing capacity type of failure ahead and below the wedge. This failure theory was based on the bearing capacity failure for deep footings. The model

helped identify an additional parameter that influenced the draught force for a backward raked tine. This parameter is the sliding resistance component on both sides and beneath the elliptical soil wedge. Results from multitine studies showed that draught force increased with tine spacing but the increase was not significant. In the wet condition the tines merely cut slots and little or no interaction was noted.

In an effort to find the optimum water level for soil puddling, a laboratory study was conducted to determine the influence of water-soil ratio on the ease of puddling air dry aggregates. Soil puddling was carried out using a rotary stirrer simulating the rotary motion of a rotary cultivator commonly used in wetland preparation. The results obtained showed that the fastest dispersion of particles resulting in a minimum wet bulk density of 1.23 Mg/m^3, was achieved at a water-soil ratio of 1.2. (A supersaturated condition equivalent to a moisture content of 120% dry basis). Increasing the water-soil ratio above this value did not change the wet bulk density value for all stirring times.

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TABLE OF CONTENTS

LIST OF TABLES.

LIST OF FIGURES

LIST OF PLATES.

LIST OF SYMBOLS

n	Porosity
Db	Clod bulk density (Mg/m^3)
Dp	Particle density (Mg/m^3)
θ	Volumetric moisture content (cm^3/cm^3)
t	Time (days)
r	Distance from the top of soil block to the wetting front (mm)
D	Water diffusivity (mm^2/day)
a	Thickness of soil block (mm)
θ_i	Initial volumetric moisture content (cm^3/cm^3)
θ_f	Final volumetric moisture content (cm^3/cm^3)
θ_t	Volumetric moisture content at any point r within the soil block at any time t (cm^3/cm^3)
N	Summation limit
e	Exponential term
I_l	Lateral infiltration (mm)
Δz	Thickness of soil layer (mm)
K	Number of soil layers
f_j	Fractional wetted depth (mm)
a_j	Fractional wetted surface area (mm^2)
t_j	Time to start of input into layer j (days)
S	Sorptivity ($mm/day^{0.5}$)
x	Length of soil core (mm)
λ	Boltzmann variable
A_v	Total ped surface area (mm^2)
θ_{sat}	Volumetric moisture content at saturation (cm^3/cm^3)
K_{sat}	Saturated hydraulic conductivity (mm/day)

p'	Spherical pressure (kN/m^2)
q'	Deviatoric stress (kN/m^2)
x_o	Loading position from dynamometer centroid (mm)
Fx	Horizontal force bridge circuit
Fz	Vertical force bridge circuit
My	Moment bridge circuit
Q	Total force on narrow tine face for lateral failure mechanism (N)
H'	Horizontal force on soil wedge (N)
V'	Vertical force on soil wedge (N)
B'	Shear force on soil wedge (N)
Q_h	Horizontal force on narrow tine (N)
V_h	Vertical force on narrow tine (N)
A_o	Critical aspect ratio
A	Tine aspect ratio
A'	Tangential adhesion per unit width (N/m)
P	Passive resistance force per unit width (N/m)
m	Rupture distance ratio
D_f	Draught force on the tine (N)
V_f	Vertical force on the tine (N)
R	Resultant force (N)
0_R	Angle of the resultant force to the horizontal (degrees)
SF	Sliding resistance on the walls of slot in upward failure mechanism (N)
Hs	Horizontal component of the sliding resistance (N)
Vs	Vertical component of the sliding resistance (N)
D_T	Total horizontal force on the tine (N)
V_T	Total vertical force on the tine (N)
r'	Crescent radius (mm)

ρ	Angle of crescent element from the direction of travel (degrees)
ρ'	Maximum angular limit of ρ (degrees)
q_o	Maximum vertical stress (kN/m^2)
K_o	Ratio of horizontal to vertical stress on the soil at rest
B	Footing width (mm)
Nc', Nq', N_γ'	Bearing capacity factors
γ	Soil dry bulk density (Mg/m^3)
z	Working depth (mm)
c	Soil shear strength (kN/m^2)
c_a	Soil metal shearing resistance (kN/m^2)
q	Surcharge pressure (kN/m^2)
$N\gamma$ (or $K\gamma$), Nc (or Kc), Na (or Ka), Nq (or Kq)	Soil resistance coefficients representing the gravitational, cohesive, adhesive and surcharge components (dimensionless)
f'	Forward rupture distance (mm)
s'	Side rupture distance (mm)
s	Soil effect
p	Back pressure (kN/m^2)
w	Width of tine (mm)
F_h	Horizontal force component (N)
V_h	Vertical force component (N)
v	Tine speed (m/s)
α	Tine rake angle (degrees)
δ	Angle of soil-metal resistance (degrees)

ϕ Angle of soil shear strength (degrees)

ψ $45+\phi/2$

$\left.\begin{array}{l} r_o \\ s_o \\ t_o \\ k \end{array}\right\}$ Constants in the force prediction models developed by Stafford (1984)

03 The angle subtending radii R1 and R2 of arc BC in Figure 6.10 (degrees)

R1 Radius of arc BC (mm)

R2 Radius of arc B'C'(mm)

S_o Effective arc length (mm)

Q_h' Horizontal force on the elliptical wedge (N)

V_h' Vertical force on the elliptical wedge (N)

$\left.\begin{array}{l} Q_1 \\ Q_2 \\ Q_3 \end{array}\right\}$ Forces acting on the elliptical wedge (N)

SR Sliding area of the elliptical wedge (mm^2)

$\left.\begin{array}{l} SF_1 \\ SF_2 \\ SF_3 \end{array}\right\}$ Sliding resistances on the elliptical wedge (N)

CHAPTER 1.0 INTRODUCTION

1.1 General

Rice is grown in 111 countries in the world and is the primary food for the majority of developing countries in Asia (Brady, 1978). Unlike other crops, rice is grown under water. It is adapted to different cultivation methods including direct seeding and transplanting. Despite the fact that direct seeding reduces the labour cost and sometimes gives higher grain yield when sown by a drill (Khan, 1975; Navasero, 1969; Jayasekara, 1966 and Adair et al., 1962), this method has certain disadvantages namely:

a) More weed growth occurs in direct seeded than in transplanted fields.

b) Uneven germination, initial stunting, slow growth and lodging of crops due to poor root development.

c) Need for a high standard of levelling and a good water control system.

In contrast to direct seeding, transplanting uses healthy and rigorous seedlings and gives a more uniform crop stand. Additional advantages are effective weed control and reduced crop lodging. Plant spacing is an important production factor in transplanted rice. Planting rice closer than necessary increases the probability of lodging. On the other hand, spacing too widely reduces yield (De Datta, 1981).

Transplanting of rice seedlings and weed growth is usually facilitated by puddling of rice fields through wet cultivation.

The soil is converted into mud under flooded condition by draught animals or powered implements. Often at this stage the water requirement is at its peak. Puddling destroys the system of macropores and results in a minimum percentage of air filled pores (Koenigs, 1963). It substantially increases the amount of water retained by the soil and reduces both the water and nutrient loss through percolation. This standing water helps control weeds, promotes oxidation-reduction conditions that favour rice growth and creates a soft medium into which to transplant rice seedlings (Sanchez, 1973; De Datta and Kerim, 1974; and De Datta et al., 1979). There is also a reduction in the apparent specific volume (void ratio) of the soil (Ghildyal, 1978). Research on soil tillage for irrigated and upland rice at the Indian Institute of Tropical Agriculture shows that for irrigated rice, wet tillage proved a better way of land preparation than dry tillage and significantly higher yields of rice were obtained. However, the water consumption and time to prepare the soil into a puddled state is very high (De Datta, 1981).

1.2 Wetland Paddy Cultivation

For paddy cultivation, several basic cultivation operations can be identified, namely loosening, mixing, inversion, compaction and levelling. After harvest and at the beginning of the rice phase, the soil is often compacted and covered with weeds or trash. Tillage must loosen the soil and control weeds through incorporation by mixing or inversion. Loosening is followed by puddling to move the organic material deeper and to reduce soil permeability at the bottom of the puddled layer.

Permeability can be reduced by mechanical soil manipulation, forcing soil particles down to decrease pore size at the bottom of the puddled layer. Levelling may be needed before transplanting.

Presently mechanical cultivation of wet paddy presents a difficult problem in developing countries where mechanisation has not been successfully practised. In countries where power resources are limited, cultivation may be done using a hand tool or in some cases by treading of animals. Animal drawn implements often consist of comb harrows or wooden or metal drums with lugs or blades. On the contrary, in countries where mechanical resources are in abundance, the land is usually cultivated dry and sowing may be carried out either by drilling in slightly moist soil, followed by irrigation, or by broadcasting over already flooded areas. In these countries, a rubber tyred tractor may be used. Tractor drawn puddlers may include a steel drum with blades, tine tillers, disc harrows or power rotary tillers aided by cagewheels. Cagewheel extensions have proved advantageous in assisting with the puddling, improving traction and pressing down organic matter.

Despite the number and types of implement currently available in the market, no standard implement has so far been recommended for creating the desired puddled layer although the rotary cultivator, disc harrow, rotary puddler and tine tiller have found increasing favour. The capacity of this equipment is low and the draught of the conventional disc harrow is high (Dutt et al., 1986).

Tillage operations are especially consumptive of energy. The consumption of energy as well as the wear and tear of tractors and implements increase sharply with working depth. The traditional and still widely practised tillage is based on a series of primary cultivations, aimed at breaking the soil mass into a loose systems of clods of mixed sizes, followed by secondary cultivation aimed at pulverisation, repacking and smoothing of the soil surface. These practices performed uniformly over the entire field often involve a whole series of successive operations each of which is necessary to correct or supplement the previous operation all at the cost of energy and water usage.

Under flooded conditions, the traditional plough merely disturbs the soil whilst soil churning, mixing, inversion and compaction are made effective by animal or human trampling. Puddling requires an input of mechanical energy; such input derives usually from a draught animal or a hand tractor, and for resource-poor farmers in particular, the cost of those energy inputs should be minimised. Efficient use of water at this stage will result in additional areas that can be supplied with the same amount of irrigation water, thus increasing the productive irrigated area. Further benefits include the more available supply of water that can be used to optimise the cropping schedule, smaller and less expensive of canal sections through reduced water requirements and more efficient management through better allocation and timely distribution of water throughout the service area (Valera and Wickam, 1977).

According to Sarker (1985), the amount of water needed to prepare land for wet rice depends mainly on soil type and water holding capacity, but most importantly on the type of land preparation. In most irrigated areas, there are two distinct tillage practices for land preparation, namely pre-irrigation tillage and post irrigation tillage. Pre-irrigation tillage is one that is described as the tilling of the field well before inundation by the irrigation water. It usually relies on residual moisture content for easy ploughing. Post irrigation tillage is the practice in which the land is tilled after irrigation water is supplied. Both practices require water for land soaking in which water is used to saturate the soils before ploughing and puddling. Generally, land soaking and land preparation (ploughing and puddling) use one third of the total water supply in the growing rice crop (De Datta, 1981).

Sarker (1985) compared pre-irrigation and post irrigation tillage techniques on a basis of water consumption, rice yields and cost of operations. Results obtained show that some farmers tilled their land as many as five times before final land preparation. Comparing figures on water use for land soaking and land preparation shows that water saving associated with pre-irrigation tillage practices is highly significant. Pre-irrigation tillage reduces the number of tillage operations after land soaking to a minimum of one, and more tilling operations are not required. On the other hand, post irrigation tillage requires at least three tillings or ploughing operations and the same number of puddling operations to prepare land for transplanting. It was found that the variations in crop yields for pre-irrigation tillage and post irrigation tillage practices were significantly different at the one percent level with pre-irrigation tillage giving the higher yields. However, the difference in costs for tillage operations between these two practices were statistically insignificant. In the light of this finding, savings in water needed for land preparation are possible by practising pre-irrigation tillage rather than post irrigation tillage.

1.3 Constraints To Improving Soil Preparation

Presently, considerable progress has been made in designing low energy implements for dryland cultivation. For wetland cultivation, however, little is known. The pressing need for design information to supplement the current qualitative procedures has demanded that methods for design be developed. Basic tools such as the traditional wooden plough date back into antiquity, yet, they are still found in their original form in many parts of the rice growing countries. Even in more advanced societies, the moldboard plough is designed by empirical methods. The tool is varied in some manner and acceptable designs are identified when the resulting soil condition is adjudged to be satisfactory. Quantitative descriptions or representations of the final soil condition are seldom used and, in addition, the forces required to move the tool are frequently not quantitatively assessed.

The success of any tillage operation depends on creating the right disturbance and this is determined by implement shape. Agricultural implements can be categorised according to patterns of soil disturbance namely wide tines (where the working width is greater than the working depth), narrow tines (where the working width is less than the working depth) and very narrow tines (where the working width is much less than the working depth), (Spoor et al., 1985a). Among the implements classified under wide tines are levelling blades, wide chisel tined plough, angled disc harrows, subsurface sweeps and blades. The narrow tine group consists of cultivation tines, tiller tines and narrow chisel tine plough, while the very narrow tine category includes harrow tines and mole ploughs.

In addition to the above, there are three more groups of implements which cover sideways angled blades, wheels or rolls and powered tines. The sideways angled blades include moldboard ploughs, disc ploughs and disc harrows, while the wheel category includes plain, peg tooth, crumbler rolls and presses. The powered tines include horizontal and vertical axis powered rotary cultivators.

Although tined implements are categorised into three groups, the disturbance caused by a given tined implement could fall into any category depending upon soil conditions (Spoor and Godwin, 1978). As tine working depth increases in a given soil, the nature of the disturbance changes from that of a wide to a narrow to a very narrow tine. The transition from narrow to very narrow tine disturbance is determined by the critical depth. As the tine moves below the critical depth, the soil disturbance at and below the critical depth changes from brittle, which loosens soil, to compressive, which compacts soil.

Over the years, there has been very little improvement in the animal drawn implements used for rice cultivation. The local wooden plough and plank seem to be the only implements used for most puddling and levelling. The introduction of tractor power has often not affected the type of implement used. Spoor et al. (1985a) reported that for efficient equipment design and selection, it is vital to have a knowledge of necessary soil condition and of the transformation needed to achieve them. Implements selected or desired must produce the required results under prevailing soil and moisture conditions and utilise minimum power and draught. In the light of the difficulty in developing new implement for wetland cultivation, advances could be made by resorting to fundamental studies under the prevailing soil and moisture conditions.

According to Gill and Vanden Berg (1968), the key to the development of a scientific approach to tillage is the establishment of a soil-implement mechanics base capable of describing and predicting the action of a tillage tool on the soil. Once a realistic soil-implement mechanics base is developed, it can serve to predict soil behaviour and help in the selection of appropriate tillage tools and in the improvement of tillage efficiency. Hence for wetland tillage research, it is vital to conduct an investigation on the reaction of wet soil to external forces imposed by agricultural implements and the energy input required while working in the wetter range. This is important since choice of implement and the level of moisture content have significant effects on the power requirement and the resultant mixture.

The reduction of water consumption has also been of great concern in many areas. Water shortage and severe drought are not new phenomena in human experience but the increasing pressure to produce more food to meet the rapidly expanding population makes efficient water management an urgent issue. With increasing demands being made on water resources worldwide for industrial and domestic use, the water available for agriculture is likely to become scarcer and costly. Hence there is a need to improve the efficiency of water use by crops and to avoid wasteful applications of irrigation water. This is desirable particularly in rice growing areas where wet cultivation is practised. This requirement is summarised by Russell (1985) who stressed the need to develop and evaluate effective techniques of wet cultivation and puddling that maintain high rice production, allow savings of seasonal water requirement and involve smaller inputs of puddling water and energy. In puddling, the water usage is often in excess to help scouring, apart from reducing the soil strength.

Maximising the use of irrigation water requires strict control on soil water usage particularly during field preparation. Another possibility is to utilise the rain water for land soaking saving the irrigation water for crop growth. For wetland cultivation, it has been recommended that pre-irrigation tillage be adopted to produce loose clods (Sarker, 1985; and Valera, 1977). Earlier work by Koenigs (1961) has shown that preparing mud from dry clods is much easier and saves water compared to preparation from the undisturbed state. For timely operation, it is always preferred to have clods that can absorb water quickly. It is not known, however, whether initial size and moisture content level have any effect on the rate of water uptake especially in cases where soil clods are wetted by capillarity rather than by complete flooding.

In dryland cultivation, maximum friability can be achieved in some soils at a gravimetric water content of about 90% of the lower plastic limit (Utomo and Dexter, 1981). Ojeniyi and Dexter (1979) have earlier reported that tillage at this optimum water content maximizes the proportion of small clods produced. However, for resource-poor farmers in the tropics, tillage is often conducted on submerged fields to reduce the draught force. In view of the limited power resources available and the need to conserve water in wetland tillage, it would be a great help if clods could be produced at a moisture content above the lower plastic limit. Experiments conducted by Spoor and Godwin (1979) indicate that brittle failure and hence clod formation can occur at higher moisture contents, above the lower plastic limit, provided confining stresses are low. The results, however, were observed in a triaxial test and were not evaluated in the field or a soil tank.

A review of existing information on rice land preparation reveals that equipment and timing of operation vary with location, soil type, irrigation water and power availability. The water use and the energy requirements due to increased number of operations are high. Whilst much work is documented on the agronomy, breeding, insect and disease control of rice, there is limited research recorded on optimum water level and the most efficient implement which creates the disturbance required. In fact very little information is available regarding the optimum soil condition before transplanting rice. Although a well prepared mud is favourable, experiments to establish the optimum moisture content to obtain such a condition are lacking. This lack of a quantitative description of the degree of puddling poses a major hindrance in performance evaluation of puddling equipment and this in turn hampers the improvement of implement design. The difficulty in quantifying the degree of change in the structure of soil brought about by wetland tillage best suited to the requirement of the rice plant, stems from the fact that very little work has been done to relate the optimum condition to the maximum yield or growth obtained with the exception of the works by Painuli et al. (1988) and Kumar et al. (1977).

To summarise, water can be better utilised when puddled conditions are prepared from dry clods than from a wet undisturbed state. Clods that saturate faster require less energy to break. The need for faster absorption is vital especially in areas where water is scarce and the time to prepare land is short. Producing dry clods requires a relatively high power requirement. Very little information is available on soil behaviour when worked in the wetter range more applicable for wetland cultivation. Fundamental work on soil-implement interactions have been mainly concentrated at moisture contents below the lower plastic limit, exceptions to this are the works of Stafford (1979), Wismer and Luth (1970), Rajaram (1987) and Owen (1988) who worked at moisture contents slightly above the lower plastic limit. Little attempt has been made to explore the possibility of producing clods within the plastic range, though, it has been indicated that brittle failure and hence clod formation at high moisture contents may be possible (Spoor and Godwin, 1979). Information is also lacking on the effect of clod size and initial moisture content on the rate of water uptake by capillarity when the soil is not completely flooded. From the above, clearly there are many potential benefits that could be gained in terms of lower power and energy requirement, better utilisation of water, faster preparation of seedbed and improved soil conditions through a better understanding of soil implement interaction and soil behaviour when loaded at higher moisture contents. This project therefore aims to explore some of the fundamental aspects of these relationships.

1.4 Objectives

The general objective of this investigation was to evaluate soil-implement mechanics under wetland condition with the aim of reducing water requirement in land preparation. The specific objectives were three-fold, namely:

i) to study water uptake by soil clods of different sizes and at different initial moisture contents under different confining stresses when wetted by capillarity.

ii) to measure the forces and observe the nature of soil failure on plane narrow tines varying in rake angles, working depth and width and working at very high moisture contents, most applicable to wetland cultivation, and

iii) to assess the influence of water quantity on the degree of puddling and final aggregate size distribution.

CHAPTER 2.0 LITERATURE REVIEW

2.1 Clod Wetting and Drying

2.1.1 Rate of Water Uptake

Considerable work has been done on clod wetting and clod drying over the past decades. Emerson and Grundy (1954) studied the effect of rate of wetting on water uptake and cohesion of soil crumbs. They wetted columns of air dry soil crumbs of 2 to 5 mm by means of siphons of finely drawn out capillary tubing dipping into a reservoir of distilled water maintained at a constant height, the rate of wetting being controlled by the diameter of the tube. Their results show that the amount of water taken up by each column increased continuously with rate of water application. This was attributed to increased aggregate immersion at the higher application rates. The corresponding progressive decrease in the cohesion of the wetted crumbs was measured by their resistance to break down under the impact of falling water drops. The loss of cohesion was described to be due to almost entirely to entrapped air, non-uniform swelling of the clay being a negligible factor in weakening crumbs. The extrapolated value of the cohesion of the grassland crumbs at zero rate of wetting was twice that of the arable, indicating an additional cohesive force in the grassland crumbs. The cohesion of the arable soil fell much more rapidly with increased rate of wetting than that of the grassland, probably because the roots in the grassland crumbs provide easy escape passages for the air. Emerson (1955) studied the difference in the rate of water uptake between soil crumbs and undisturbed soil cores at low suctions. The soil was dried to wilting point before the test. Results obtained show that the decrease with time of water uptake was slower for the undisturbed core than the crumbs (Figure 2.1). He attributed this observation as due to the absence of cavities into which the clay crystals could expand.

Gumbs and Warkentin (1972) studied the effect of bulk density and initial water content on water infiltration into clay soil samples. Infiltration measurements were made on swelling clay samples packed into columns. Small increase in bulk density over the range 1.10 to 1.25 Mg/m^3, markedly decreased the rate of water infiltration. The magnitude of the effect was greater for confined samples than unconfined samples at all initial water contents. A 1 cm thick compact layer in the profile was sufficient to retard water movement if the sample was confined. In partially confined samples, the soil in the compact layer would swell on wetting and water movement was retarded only when the bulk density (after swelling) still exceeded the bulk density of the remainder of the column. Comparison of horizontal and vertical infiltration showed that under their experimental conditions, gravity contributed significantly to water movement at high initial water contents. Following from the above study, Gumbs and Warkentin (1976) measured the bulk density changes, final degree of saturation, volume increase on wetting and rate of wetting of aggregates and clods varying in size from 50 mm to 3.6 mm in diameter. The soil used was a silty clay loam. The results showed that on wetting, dry bulk density decreases were greater in the small clods than in the large ones.

Olsen (1960) measured an exponential increase in clod permeability with increasing porosity whilst Millington and Quirk (1959) and Philip (1957a) found that permeability increases exponentially with increase in initial moisture content. Philip (1957b) has shown that the rate of advance of the wet front increases and the rate of infiltration decreases with increasing initial moisture content for both short and long duration wetting. Hanks and Bower (1962) and Miller and Gardner (1962), found that when there is textural layering in a profile, infiltration is controlled by the less permeable layer.

2.1.2 Shrinking and Swelling Behaviour

The shrinking of clay soil on drying and its swelling on wetting have been described by many researchers (Haines, 1923; Holmes, 1955; Keen, 1931; Lauritzen and Stewart, 1941; Lauritzen, 1948; and Stirk, 1954). Haines (1923) observed that during the drying of a remoulded block of a saturated clay soil, the decrease in volume was initially equal to the volume of water lost so that the block remained saturated as drying proceeded. The first stage called 'normal' shrinkage by Keen (1931) was followed by 'residual' shrinkage (Haines, 1923) when the volume decreased less rapidly than the water content as air entered the soil. These stages are presented in Figure 2.2 in the drying curves for blocks moulded by Holmes (1955) from soil containing 64 percent of clay. Holmes found that the matric potential at which the transition from normal to residual shrinkage occurred in his remoulded clay soils was of the order of -10^4 J/kg (-100 bar). Macroscopic shrinkage ceased at about -10^5 J/kg (-1000 bar). Stirk (1954) showed that the lower the clay content, the higher the potential at this transition. Lauritzen and Stewart (1941), Lauritzen (1948) and Stirk (1954) worked with naturally structured soil rather than remoulded blocks. They noted that, at the start of drying, there was an initial stage, called structural shrinkage (Stirk, 1954), during which air entered large pores and cracks while the bulk volume of the soil decreased.

Spoor et al. (1985b) conducted a laboratory investigation examining the influence of the degree of reworking and subsequent ageing period before rewetting, on the unconfined swelling behaviour of soils of different depositional origin, mineralogy and bulk density. All the soils exhibit unconfined swelling tendencies, these increasing considerably following soil reworking. Unconfined swelling following reworking is excessive in soils high in exchangeable sodium and high in the calcareous alluvial and lacustrine soils and in the lower density, non calcareous, non alluvial soils. No clear pattern emerges regarding the soil properties influencing ageing effects. The percentage swelling reduction as a result of ageing tended to be greater for the first 7 days ageing period than for the subsequent 14 to 21 day period.

2.1.3 Stability of Aggregates

Harris et al. (1966) reported some work on the stability of aggregates conducted earlier by Alderfer (1950) and Rennie (1952). Alderfer (1950) studied the stability of aggregates at different moisture contents obtained by slowly drying premoistened aggregates and by slowly wetting air-dried aggregates. Aggregate stability decreased as moisture contents increased beyond field capacity. The stability of oven-dried aggregates was higher than that of aggregates in the air-dry state. Rennie (1952) as cited by Harris et al. (1966) found that aggregates were more stable to wet sieving when they were prewetted slowly with an atomiser spray than by capillary action. However, both were least stable when immersed directly in water.

Marshall and Holmes (1979) reported that the stability of aggregates decreases on wetting dry soil particularly if done rapidly. This could be due to the following reasons:

a) The strength of soil decreases with water content because of reduced cohesion and the softening of cementing agents between the soil particles.

b) If macroscopic swelling occurs during adsorption, this will cause uneven strains throughout an aggregate so that its structure will be distorted and weakened. This effect of uneven wetting will be greatest when dry clay soil wets rapidly (Panabokke and Quirk, 1956).

c) Rapid wetting of dry soil can cause disruption by air trapped by water that fills the outside pores of aggregates before advancing inwards. If air compressed by this advance reaches a pressure greater than the tensile strength of the soil, it escapes explosively breaking off fragments in doing so as can be observed when dry aggregates are immersed suddenly in water. This causes slaking of many soils particularly those of low or medium clay content (Yoder, 1936; Henin and Santamaria, 1975; Russell, 1938; Robinson and Page, 1950; Mazurak, 1950; and Emerson and Grundy, 1954).

Dettman (1958) experimented on the water uptake by pure clays and crumbs and concluded that entrapped air is neither a necessary nor an important factor in their slaking. Slaking is always associated with rapid intercrystalline swelling of the clay. If swelling is suppressed or takes place slowly, slaking does not occur and it is suggested that slow swelling gives time for readjustment of the internal geometry of the clay, so producing some dislocation but no disruption.

Mc Intyre and Loveday (1968) found that rapid wetting of dry unconfined clods from expansive soils (usually containing more than 30% clay) resulted in a significantly greater retention of water than when clods were wetted slowly. The clods in both cases were drained to equilibrium at suctions up to 600 cm. Slow wetting by capillarity from water under a suction is commonly used to allow air to escape freely and so avoid explosive damage to weak aggregates. Kemper and Koch (1966) showed that the percentage of stable aggregates was usually much lower when samples were immersed rapidly in water compared to wetting under suction. Their results are presented in Table 2.1.

2.1.4 Clod Strength

Soil clods become weak on wetting and hard on drying. The factors affecting clod strengh have been reported by several authors notably Towner (1987a and 1987b), Salih and Maulood (1988) and Rogowski and Kirkham (1976). Towner (1987a) described investigations on the mechanics of cracking of drying clay. Bars of clay were allowed to dry from different initial water contents but prevented from shrinking in the longitudinal direction. Their water contents were measured when they cracked and were found to be essentially the same, regardless of their initial water content. Parallel experiments were performed to determine the tensile strength of the clay as a function of water content and the soil water suction as a function of water content. The tensile stress generated by the shrinkage was found to be related to the total change in soil water suction when the shrinkage is isotropic. Towner (1987b) further studied the mechanics of the stress system leading to cracking. The clay cracks at a unique moisture content which is independent of the initial moisture content and can be determined if the relationship between tensile strength and water content is known.

Salih and Maulood (1988) studied the influence of temperature and cycles of wetting and drying on modulus of rupture. Modulus of rupture decreased with increase in temperature of drying and correlated strongly with the degree of shrinkage of soil briquets. Low shrinkage in soil briquets coincided with a low modulus of rupture. Rogowski and Kirkham (1976) observed that aggregate strength decreased with size and large increases in clay content were accompanied by large increase in strength.

2.1.5 Modelling Water Infiltration Into Soil Clods

The prediction of water infiltration into field soils has been described by a number of researchers (Davidson et al., 1963; Gupta and Staple, 1964; Rawlins and Gardner, 1963; and Staple and Gupta, 1966) who use the diffusion equation to predict infiltration into columns of soil. Philip (1968) proposed a theory for infiltration into well aggregated soils and concluded that the size of the soil aggregates must be large and the permeability of the aggregates must be low for this theory to be valid. The applicability of this theory was later tested by Gumbs and Warkentin (1975) with aggregated clay soils and they concluded that the classical diffusion equation can be used to predict infiltration provided the correct diffusivity and conductivity values were used. Gumbs and Warkentin (1976) further proposed a prediction model on the rate of saturation of spherical aggregates using an equation analogous to heat conduction. Based on linear flow of heat into a solid slab (Carslaw and Jaeger,1959), the entry of water into a cubical clod could be described as the following;

$$\frac{d\theta}{dt} = \frac{Dd^2\theta}{dr^2} \qquad 0 < r < a,\ t > 0 \qquad ......(2.1)$$

where θ = volumetric moisture content,

t = time,

r = distance from the surface of the solid to the wetting front,

D = water diffusivity,

a = thickness of the solid block of soil.

With the following initial and final boundary conditions

$$\theta_i = 0 \text{ when } t = 0,\ 0 < r < a \qquad ....(2.2)$$

$$\theta_f = \theta_{sat} \text{ when } r = a,\ t > 0 \qquad ....(2.3)$$

equation (2.1) has the following solution

$$\theta_t = \theta_i + (\theta_f - \theta_i)r/a +$$

$$2/3.14 \int_{N=1}^{N=\infty} \theta_f(\cos N3.14) - \theta_i/Ne^{(-D(N3.14/a)^2 t)} \sin(N3.14r\ /a)] +$$

$$2/a \int_{N=1}^{N=\infty} \sin N3.14r/a e^{-D(N3.14/a)^2 t} \quad \ldots\ldots\ldots\ldots(2.4)$$

where θ_i= initial volumetric moisture content,

θ_f= final volumetric moisture content,

θ_t= volumetric moisture content at any point r in the soil block at any time t,

θ_{sat}= volumetric moisture content at saturation.

Jarvis and Leeds-Harrison (1987) described a two domain model of water movement in drained clay soils which incorporate lateral sorption into soil peds given by

$$I_1 = \sum_{j=1}^{j=k} (\Delta z f_j)(a_j A_{vj})(S_j/2)(t-t_j)^{-1/2} \quad \ldots\ldots\ldots(2.5)$$

where k is the number of soil layers, Δz is the layer thickness, f_j, a_j, t_j and S_j are the fractional wetted depth, the fractional wetted ped surface area, the time to start of input into layer j and sorptivity respectively. The sorptivity value, S_j, is difficult to determine in a laboratory condition using compacted and structureless clay.

To summarise, the results of past investigations show that water uptake decreased with wetting time and the decrease was slower for undisturbed cores than surface clods. Water movement was more influenced by gravity when wetted from high initial water contents. Clay mineralogy alone was found to have no direct relationship with percentage volume change of soil clods on wetting. Swelling on wetting was reduced as soils aged after disturbance for the first seven days than after longer periods. The dry bulk density decreases were greater in the small clods than in the large ones when clods were wetted. During drying, soil experienced normal and residual shrinkage. In normal shrinkage, the volume change was equal to the volume of water lost while in residual shrinkage, the volume decreased less rapidly than the water content as air entered into the soil. Soil aggregates were found to be more stable when wetted slowly rather than when immersed in water. Aggregates stability decreased as moisture contents increased beyond field capacity and the stability of oven dried aggregates was higher than that of aggregates in the air dry state. Aggregates were also observed to lose strength on wetting but gained enormous strength on drying. The modulus of rupture decreased with increase in temperature and correlated strongly with the degree of shrinkage. Clod strength decreased with size but increased with clay content. The rate of advance of the wetting front depended on permeability, changes in bulk density, layering in the profile and on initial water content of the soil. Water infiltration models have also been proposed. The infiltration models related to this study are those proposed by Gumbs and Warkentin (1976) but modified to consider the linear flow of heat into a solid bounded by a pair of parallel planes and the lateral sorption model of Jarvis and Leeds-Harrison (1987).

2.2 Soil-Tine Interaction Studies

2.2.1 Soil Failure by Single Tines

It can be stressed that there are three types of failures caused by agricultural implements, namely brittle, flow or compressive and tensile failures. Hettiaratchi (1987) has demonstrated how this transition can be explained in terms of the state paths generated to cross the critical state line in the critical state model of soil mechanics. In the critical state model, failure is of a brittle type if the stress path meets a failure plane from the dry side (Hvorslev surface) of the critical state line and compressive if the stress path approaches from the wet side (Roscoe surface) of the critical state line. The crucial parameter determining the failure mode is the magnitude of the spherical pressure. Considerable evidence has shown that the spherical pressure governs the transition from compressive to brittle behaviour (Spoor and Godwin, 1979); Robinson (1959) and Heard (1960). Hettiaratchi (1987) pointed out that moisture content, soil strength, volume change, cohesion and soil microstructural state influence the variable p' (confining or spherical pressure) which controls the transition. This confirms earlier work by Stafford (1984) who observed that the transition can be determined by moisture content, soil density, tine speed and rake angle. The effects observed were later explained in terms of the critical state concept, particularly by the relationship between p' and q' (deviatoric stress).

The nature of soil failure created by wide blades and narrow cutting tines has been studied by a number of workers at moisture contents below the lower plastic limit. The classic form of failure generally attributed to plane tines has been that in which a distinct shear or a failure plane runs from the base of the blade up to the soil surface ahead of the tine in a repeating pattern (Soehne, 1956). Thus the primary failure pattern is of large clods. A localised shear plane extended from the base of the tine and in front there was a crescent shaped block of failed soil. This pattern has been recognised by many researchers notably Payne (1956), Payne and Tanner (1959) and Godwin (1974). However, departures from this pattern have also been noted. Olson and Weber (1985) and Stafford (1981) reported that the nature of soil failure caused by narrow tines changed from periodic creation of shear planes to continuous flow as the speed of the tine was increased. Four types of failure were noted by Elijah and Weber (1971); shear plane, bending, tensile and flow. Rajaram (1987) while working with a plane tine in a clay soil observed that the soil in front of the plane tine failed either by collapsing, cracking, in chip form or readily yielding and flowing up and around the tine depending on the moisture content. Stafford (1984) observed no distinct shear planes in flow failure. Seliq and Nelson (1964) on the other hand observed failure phenomena associated with various tine configurations in different soils. They reported two principal mechanisms of soil failure, passive shear failure and tensile failure or splitting.

Following earlier work by Zelenin (1950) and Miller (1971), Godwin (1974) observed two failure mechanisms in his soil failure studies of very narrow tines. These consist of an upper failure zone where the displaced soil has forward, sideways and upward components, termed crescent failure, and a lower failure zone where the displaced soil has components both in the direction of travel and sideways,termed lateral failure. The transition between these two failures is determined by the critical depth which is influenced by tine aspect ratios, soil condition and tine inclination angle. With tines of small aspect ratio, the soil ahead of the wedge on the tine face moved forwards and upwards over the entire working depth with a distinct shear plane being developed from the tine base (crescent failure). As the tine aspect ratio increased, the soil below a certain depth (critical depth) appeared to move forwards only with no distinct shear plane being formed (lateral failure). Crescent failure occurred above this depth, with the distinct shear plane developing from the critical depth. A decrease in tine rake angle caused an increase in the critical depth for a fixed tine aspect ratio. Loose soil above a compact , denser soil also increased the critical depth. The existence of a critical depth below which little soil loosening occurs was later confirmed by Owen (1988) and Spoor and Fry (1984).

The existence of soil wedges and compacted cones were earlier observed by Nichols and Reaves (1958), Tanner (1960), Miller (1971), Godwin (1974) and Johnson (1977) using glass sided soil tanks. In field conditions, the soil wedges and cones were noted by Tanner (1960) and Willatt and Willis (1965) . Tanner (1960) noted that for tines between 76^0 and 90^0 rake angles, soil was compacted in front of the tine at depth and along most or all of the length of the tine. He was working with sand, sandy loam and clay soils. There was an upward displacement both of the compacted soil and of the looser soil in front of the tine, occurring over most of the working depth. At the level of the tine tip, there was zero vertical displacement. Crescent shear surfaces were not clear, though sometimes suggested in the sandy loam. Miller (1971), however, observed two failure zones in dry sand, an upper zone (corresponding to crescent failure) in which displacement occurred sideways and upwards and a lower zone of horizontal displacement only. This was confirmed by Godwin (1974) and Johnson (1977) in a friable sandy loam and observed distinct crescent failure planes. Godwin (1974), showed that the critical depth of transition between the zones increased as the tines were raked further forward, increased with tine aspect ratio and increased as a constant function of tine width only for vertical tines of high aspect ratio.

Wedges and compacted cones form in field soils on tines of all rake angles, their shape depending on tine rake angle (Tanner, 1960). Large cones were observed on the underside of the backward raked tines which may have accounted for their ability to create crescent failures. Formation of a moving soil wedge, and a stationary cone within the wedge, may account for the variation in angle of the resultant force to the normal to the tine with different rake angles, as noted earlier by Willatt and Willis (1965) and later by Omer (1977). Godwin (1974) found that the profile of a soil wedge in sandy loam conformed well to the middle line position of the shear plane predicted by Rankine active state analysis. The stresses ahead of the tine, and soil cones near the tine tip, were located at a position predicted by an equation for the depth of maximum pressure, (Zelenin, 1950), marking the transition between upward and downward displacement.

Johnson (1977) observed soil cones on tines at 30^0, 60^0 and 90^0 rake angles and soil being displaced above or below the cones. At rake angles of 60^0 and 90^0, he observed soil wedges moving up the tine, meanwhile being reformed from the surrounding soil.

During the study of soil behaviour under a single cage wheel lug in wet clay soil (Salokhe and Gee Clough, 1988 and Zhang and Shao, 1984) the failure pattern in front of the lug was totally different from that assumed in passive soil pressure theory. The deformation zone consisted of two zones namely, an 'elliptical' soil wedge and the heart shaped zone of plastic deformation. The shape of the soil wedge in front of the cagewheel lug was found to be elliptical. No transition zone or Rankine passive zone existed.

2.2.1.1 Factors Affecting Draught and Vertical Forces

From the literature review, the factors affecting forces on tines as identified by previous researchers, include tine rake angle, tine width, working depth, speed and also moisture content. The effects of inclining tines forward and backwards were first reported by Zelenin (1950). Forward inclination (less than 90^0) reduced draught force. Payne and Tanner (1959) systematically studied the effects of rake angle for narrow tines varying from 1.5 to 6.0 in aspect ratio with angles from 20^0 to 160^0 in wet sand, sandy loam and clay loam. They observed that draught force increased with rake angle and the rate of increase was greater with tines of more than 50^0 rake. The resultant force acted downwards on the tine at very acute rake angles and upward on vertical and backward raked tines. The relationships obtained between rake angle and draught force were confirmed by Tanner (1960), Dransfield et al. (1964), O'Callaghan and Mc Cullen (1965), Godwin (1974) and Omer (1977). Tanner (1960) used sand, sandy loam and clay soils with tines having an aspect ratio of 5.0. Dransfield et al. (1964) on the other hand used a hard compacted clay. The much greater variability of results in clay as obtained by Tanner was attributed to adhesion and to changes in the size of the stationary cone on the tine face. Wismer and Luth (1970), however, reported that in water saturated clay soil, the tine rake angle had an increasing linear effect on draught force.

Further results on the tine rake angle and draught force relationships were reported by Godwin (1974), Omer (1977) and Stafford (1979). Godwin (1974) made a thorough study of the crescent and lateral failure regimes in a friable sandy loam caused by tines with a wide range of aspect ratios, mounted at rake angles of 45^0, 67.5^0 and 90^0. Draught force was found to increase with rake angle and the increase became more rapid at angles above 50^0 to 60^0. This was due to the greater force from crescent failure at the steeper rake angles and the greater proportion of lateral failure, as opposed to crescent failure, as rake angle increased beyond 60^0. The direction of the vertical force changed from upwards for a vertical tine to downwards for tines raked forwards. Omer (1977) investigated similar tine performance in a plastic, cohesive artificial soil and observed that the draught force increased with rake angle for shallow working depths. The increase in draught between 45^0 and 67.5^0 rake angles was insignificant, but that between 67.5^0 and 90^0 was considerable, confirming the results of Payne and Tanner (1959).

For the 12.5 mm and 25.4 mm wide tines at the three rake angles, a minimum value of draught force was observed at 67.5^0 rake angle but a large maximum value at 45^0. The vertical force was positive at 90^0 rake angle and negative for the forward inclined tines, confirming Godwin's earlier observation. Stafford (1979) on the other hand conducted a study on the performance of a plane tine of 40 mm width over a wide range of soil moisture contents and speeds, in both clay and sandy soils. For the clay soil in the higher moisture regime, it was observed that the draught force of the 45^0 rake angle tine was greater than that of the 90^0 tine, the effect increasing with speed. The more normal effect of rake angle on draught force was observed in the lower moisture regime below the lower plastic limit. Related work conducted in cohesive soils is shown in Figure 2.3.

The effect of moisture content on force was reported by Stafford (1979) and Rajaram (1987). Stafford (1979) conducted his experiments at two moisture contents below the lower plastic limit in sandy clay loam; while for the clay soil, one of the four moisture contents used was above the lower plastic limit. Results showed that at the low moisture content, the draught force increased at an increasing rate with speed, while at the higher moisture content, above the lower plastic limit, the draught force increased at a decreasing rate with speed and tended towards an asymptotic value (characteristics of lateral failure).

Another factor affecting draught force is speed and this was studied by Payne (1956) whose results were later confirmed by Dransfield et al. (1964) and showed that draught force was insensitive to speed in loose soil but there was a significant increase with speed in compacted soils. This phenomenon was further investigated by Stafford and Tanner (1976) and Stafford (1979). At high speed the failure in both wet and dry soils appeared to be a continuous flow of soil and the draught-speed relationship was exponential, irrespective of tine rake angles. At very slow speed, the difference between brittle and flow failure pattern was marked between wet and dry clay, but in sandy soil the failure pattern was mainly brittle. Related work conducted in clay soil is given in Figure 2.4.

The effect of tine width on draught force is considerable. Payne and Tanner (1959) observed that draught was roughly proportional to tine width at acute rake angles, but became independent of width for obtuse rake angles. The increase of draught with width was later confirmed by Godwin (1974) and Omer (1977). This increase is due to a greater tine face area on which pressure acts. The rate of increase, however, falls off at greater widths (lower aspect ratio) because the proportion of crescent failure to lateral failure (which produces greater draught) increases. The vertical force shows a similar relation to tine width, the increase becoming less marked at greater widths (lower aspect ratio). Figure 2.5 shows the relationship of draught force with tine width.

Work on the effect of depth on force has been reported by several investigators. Dinglinger (1927) found that below a certain depth, the horizontal cutting force increased more rapidly (a parabolic relationship). This was later confirmed by Zelenin (1950), Wismer and Luth (1972) and O'Callaghan and

Farrelly (1964). Dinglinger used wet sand whilst Zelenin and Wismer and Luth worked in a clay soil. O'Callaghan and Farrelly on the other hand used sandy loam and clay loam. Kostritsyn (1956) , however, found that draught increased linearly with depth when cones and knives were moved through a cohesive soil (Figure 2.6). Dransfield et al. (1964) obtained similar results with a vertical tine in a loose soil and this was later confirmed by Omer (1977). Godwin (1974), however, observed that draught force increased at an increasing rate while the vertical force increased more slowly at greater working depths, because greater proportions of the tine were in the region of lateral as opposed to crescent failure. The work of Omer (1977) and Wismer and Luth (1972) are presented in Figure 2.7.

2.2.1.2 Soil Failure Theories

A number of force prediction models have been developed by various researchers for the prediction of tine and blade forces in the last decade. Existing theories of the action of tines on soil assume soil failure patterns occur principally by brittle shear under the action of compressive and shear stresses and scouring at the tine face. A degree of compaction is also envisaged against the tine face and laterally at depth as often observed in friable or loose soils (Rathje, 1931; Payne, 1956; Ede, 1956; O'Callaghan and Farrelly, 1964; Hettiaratchi and Reece, 1967; Godwin, 1974; Godwin and Spoor, 1977; and Mc Kyes and Ali, 1977).

Soil engaging implements have been classified as blades, narrow tines and very narrow tines. The soil failure for a blade is two dimensional (forwards and upwards) with small end effects which are usually ignored. For narrow tines, the soil failure is three dimensional with the soil moving forwards, upwards and sideways in a crescent shape, the end effects being very significant. The soil failure for a very narrow tine, however, consist of a small three dimensional crescent close to the surface but at depths below a critical depth, the soil failure changes to a two dimensional lateral pattern, moving both forward and sideways and being influenced by the tine geometry and soil condition. Figure 2.8 shows a simple tine geometry and Figure 2.9 shows the implement classification and disturbance.

According to Payne (1956), blades are those implements with a depth/ratio of less than 0.5 and narrow tines having a depth/width ratio greater than 1.0. Godwin and Spoor (1977), however, show that very narrow tines can be classified as tines with depth/width ratio greater than 6. Critical depth increases with decreasing rake angle, decreases with increasing soil moisture content and decreases with decreasing soil bulk density.

The theoretical models adopted for wide cutting blades have been based primarily on passive earth pressure theories for the movement of vertical retaining walls and bearing loads for footings where a dead wedge of soil is formed. The retaining wall failure is characterised by shearing and heave ahead of the tine, with the limiting shear plane sloping forward and upwards from the bottom of the tine to the soil surface at an angle of $(45-\phi/2)^0$ so as to minimise the horizontal force. A succession of shear planes are formed as blocks of soil separate from the soil mass, so that the forces on the tine are of a periodic nature. Siemens (1963) and Osman (1964) demonstrated that the logarithmic spiral technique developed by Ohde (1938) for rough passive retaining walls predicted the disturbances and force relationships for cutting blades with reasonable accuracy. The major problem with the logarithmic spiral technique is that it requires a number of lengthy trial solutions to determine the minimum passive force.

Reece (1965) proposed a simple additive equation of the form

$$P = \gamma z^2 N_\gamma + czN_c + c_a zN_a + qzN_q \quad ......(2.6)$$

where γ = soil dry bulk density

z = working depth

c = soil shear strength

c_a = soil metal shearing resistance

q = soil surcharge

N = dimensionless number

representing the gravitational, cohesive, adhesive and surcharge contributions to the force, P, acting on an interface at depth, z. This equation was applied to a wide cutting blade by Hettiaratchi et al. (1966) with N factors determined on the basis of a failure plane of logarithmic spiral form. A later more rigorous solution (Hettiaratchi and Reece, 1974) used the methods of Sokolovski (1965) to solve the equations of equilibrium for the coefficients of the four terms in the above equation. Where speed is included, the horizontal component of the inertial force can be added to the general soil mechanics equation. According to Stafford (1979), the cohesive component of Reece's additive equation accounts for 90% or more of the peak force exerted on the tine in soils with appreciable cohesion.

Where the working width is narrow compared to working depth (aspect ratio greater than one), a three dimensional analysis is necessary and semi-empirical models have been proposed by Payne (1956), O'Callaghan and Farrelly (1964), Hettiaratchi and Reece (1967), Godwin and Spoor (1977) and Mc Kyes and Ali (1977). The model of Payne (1956) is based on the separation of a soil wedge immediately ahead of the tine which continues to move up the face of the tines at rake angles less than 100^0 and being formed by fresh soil below. The two faces of the wedge act as oblique retaining walls, shearing and heaving soil upwards and outwards within a crescent-shaped region, limited below by shear planes extending forward, upwards and outwards from the bottom of the tine (Figure 2.10). Payne predicted the forces and disturbance using retaining wall theory. Both were predicted with acceptable accuracy for a wide range of soils with the exception of the forces produced by very narrow tines. The major limitations were that the model used a numerically complex solution which was very time consuming and held only for vertical tines.

O'Callaghan and Farrelly (1964) and later O'Callaghan and Mc Cullen (1965) attempted to distinguish between narrow and wide tines and introduced into the calculation procedure the concept of critical depth (Figure 2.11). The model assumed soil failure to consist of a narrow retaining wall near the surface and a bearing capacity failure at depth. In order to simplify the calculations, and because of the generally very significant effect of cohesion, the soil was assumed weightless. The cohesive component was determined by a logarithmic spiral analysis for bearing capacity, as suggested by Prandtl (1920) and Meyerhof (1951). The relatively simple equations are quick to solve and give reasonable predictions for tines 50 to 100 mm wide at depths to 175 mm. The major limitations are the limited range of rake angles over which the model applies and the very small vertical force component, which for vertical tines arises from the retaining wall section. It also disregards the weight component and assumes that there is no pressure on the soil face at the rear of the bearing capacity zone (the soil is unrestrained at depth).

Hettiaratchi and Reece (1967) on the other hand, considered the retaining wall and bearing capacity failures to be acting simultaneously over the same tine depth (Figure 2.12). The general soil mechanics equation was used to predict the retaining wall section and a modified bearing capacity equation was used to predict N factors for the lateral forces. The authors attempted to predict the rupture distance to both the front (f') and to the side (s') of the crescent, but with limited success. The major benefits of this model are that the use of N factors significantly speeds the calculation of forces and that soil weight is included as a factor in the model. This, together with the inclusion of a term for back pressure (p) on the soil failing in a bearing capacity mode, enables reasonable predictions for 50 mm wide tines operating from 50 mm to 300 mm deep. The major limitations of the model are that the failure pattern does not model the true crescent condition and the compensation for smaller rake angles is too great. Whilst it predicts accurately for narrow tines, it significantly underestimates the forces for narrower tines. This is due to the model assuming that the force increases almost linearly with width, which is not true, due to the change in soil failure patterns from very narrow to narrow tines (Figure 2.13). The vertical force component is also very small.

Godwin and Spoor (1977) and later Godwin et al. (1985) developed models to predict the forces of very narrow tines. The models resulted from extensive soil bin observations of soil failure pattern changes with changes of tine depth, width and rake angle. Depth/width ratios varied from 1 to 30 and rake angles from 45^0 to 90^0. The models assumed crescent failure above a certain depth, called the critical depth. Below this depth, lateral failure around the tines occurred. The crescent force is predicted using the general soil mechanics equation. This is estimated by integrating the force components in the direction of travel of the segments ($\delta\rho$) around the two crescent flanks and adding them to the component of the simple blade of width, w, immediately ahead of the tine. The lateral failure component is calculated from the bearing capacity solution of Meyerhof (1951) but assumes that the logarithmic spiral develops to the maximum width for which the relevant N factors are given (Figure 2.14). The major limitation of these models is that some empirical data on crescent size is needed to be able to estimate the forces. A graph of critical depth/width ratio versus actual depth/width ratio is provided to enable critical depth estimates to be made for friable soils. It is possible, however, to predict critical depths by minimising the total draught force between the crescent and the lateral failure components. The model of Godwin et al. (1985) simplifies the crescent failure pattern and enables the forces on interacting tines to be predicted. Both models predict changes in force pattern with width and realistically estimate the vertical force for a range of rake angles.

The model of Mc Kyes and Ali (1977) is very similar to that of Godwin and Spoor (1977) but an alternative attempt was made to determine the draught force without the need for empirical data on the crescent size. The draught component of the crescent force on the implement is predicted by integrating elemental force segments from passive retaining wall theory, using trial wedges. This results in N factors which are dependent on the depth/width ratios of the implement and these are presented in graphical form for depth/width ratios between 0 and 20, rake angles between 0^0 and 90^0 and angles of soil shear strength between 0^0 and 45^0. It is assumed that the angle of soil-metal shearing resistance is two-thirds of the angle of soil shear strength.

Perumpral et al. (1983) developed a mathematical model for predicting the behaviour of narrow tillage tools in soils based on a limit equilibrium analysis. The model described is similar to that developed by Ura and Yamamoto (1978) for predicting the behaviour of anchors in sand. One major difference is that the effect of cohesional and adhesional characteristics of the soil are included. The model incorporates the three dimensional aspect of the problem by considering the total crescent formation in front of the tool. For simplicity, the side crescents were replaced with a set of forces on either side of the centre wedge. The curved sliding surface was assumed to be straight. The agreement between predicted and observed values for draught and vertical force was good.

Stafford (1984) developed force prediction models for brittle and flow failure of soil by draught tillage tools. The approximate force prediction equations for flow failure for a tine of width w, are given as:

Horizontal force, $F_h = wz(r_o + s_o \log(1 + t_o v))\, k \sin(\alpha + \delta)$ ..(2.7)

Vertical force, $F_v = wz(r_o + s_o \log(1 + t_o v))\, k \cos(\alpha + \delta)$ ..(2.8).

where r_o, s_o and t_o are constants and δ is a function of tine speed, v. The coefficient, k, cannot be determined analytically because the failure boundary geometry is indeterminate, but Stafford recommended that k should lie between 7 and 8. For brittle failure, the prediction equations for forces acting on a tine are as follows:

$$F_h = w\,(czk)\sin(\alpha + \delta) + \frac{\gamma a v^2 \sin\alpha \cos(45 - \phi/2)}{g \sin(\alpha + 45 - \phi/2)} \quad \ldots(2.9)$$

$$F_v = w\,(zck)\cos(\alpha + \delta) + \frac{\gamma a v^2 \sin\alpha \sin(45 - \phi/2)}{g \sin(\alpha + 45 - \phi/2)} \quad \ldots(2.10)$$

where k, δ and a are functions of tine speed. Only the cohesive component is considered since it accounts for 90% or more of the peak force exerted on a tine (Stafford, 1979). Overall the predictions of the proposed models were in good agreement with the experimental data. The models are sensitive to soil parameters the most important being c and δ for flow failure and in the case of brittle failure, ϕ.

Swick and Perumpral (1985) developed a model for predicting narrow tillage tool behaviour in artificial soils under dynamic conditions. This model is a modification of an earlier model previously developed for slow moving tools and it includes the shear rate effect on soil shear strength and soil metal friction. The results obtained reveal that in general the predicted values tend to be lower than observed values. The authors noted that, for a few cases, the model greatly over-predicted the draught force while for others it greatly under-predicted the draught. They attributed this to under and over predictions of the size of the failure wedge. A possible reason for this tendency is the replacement of the actual curved rupture surface with a plane in the model. The angle of internal friction, soil metal friction, cohesion and adhesion were found to be independent of shear rate for an artificial soil tested. The observations contradict the findings by Rowe and Barnes (1961) and Stafford and Tanner (1983a, 1983b). The difference in the soil type, as well as the differences in the loading conditions imposed during the experiments probably account for the differences in results. They also concluded that terms including accelerational force effects can account for a large portion of the increase in tool force observed to occur with an increase in tool speed. This contradicts the findings of Siemens et al. (1965), Rowe and Barnes (1961) and Wismer and Luth (1972) who used Sohne's equation (1956) to predict accelerational forces. It is believed that these investigations used the equation to predict the accelerational force component and then added this component to the static component in contrast to Swick and Perumpral (1985) who included the accelerational forces when summing all forces on the failure wedges.

Another common observation is the downward displacement and compaction below the tip of the tine if it is narrow and sufficiently deep. This, however, does not affect the reaction force on the tine enough to be considered in the theoretical models but has frequently been observed for vertical and backward raked tines (Tanner, 1960).

The critical soil property in all these models is shear strength (Stafford, 1979) and force prediction is much less sensitive to soil weight, interface adhesion or the assumed shaped of the failure surface (Mc Kyes and Ali, 1977). Accurate measurement of shear strength is thus a prerequisite to the use of the models described. In developing the models, most researchers worked with rigid plastic material and made three assumptions, namely:

a) yielding of soil in shear obeys the Mohr Coulomb criterion,

b) a distinct rupture surface forms in front of the tine, bounded by a volume of soil in a state of plastic equilibrium, and

c) rate effects on the relevant soil parameters are negligible.

The first assumption has been shown to be approximately true for all soils, except under some extreme conditions such as very high normal stress. According to Stafford (1984), the assumption of a localised failure surface is often not justified. This is because a distinct failure surface is associated only with brittle failure occurring in dry, compact soils. Where soil is wet or confining stresses are high, then the soil yields plastically with the degree of deformation falling off with increasing distance from the interface. No distinct shear planes are evident in the soil around the interface. Deformation of soil is accommodated primarily by compression into the sides and base of the furrow and by generalised flow nearer to the free surface. According to Stafford (1984), boundary conditions can only be defined around the tine and at the free soil surface. The soil forces acting on the interface are proportional to the yield stress of the soil and to the width and working depth of the interface. At zero normal stress, cohesion is the yield stress. As soil blocks are not being formed and accelerated to the speed of the tine, inertia forces are much lower in flow failure than for brittle failure.

Where a distinct failure surface is formed, soil within the failure surface is also observed experimentally to undergo very little plastic yielding. Initial failure leads to movement of the block of soil bounded by the failure surface as a whole. This tendency for dead zones to form within the soil failure boundary has been recognised by Hettiaratchi and Reece (1975). They modified their earlier models (Hettiaratchi et al., 1966; and Hettiaratchi and Reece, 1974) to take account of these boundary wedges. The assumption that rate effects are negligible is not reasonable for prediction of tine forces at practical speeds. The draught force of moldboard ploughs is known to increase in proportion to the square of speed due to soil inertial forces. The draught forces of narrow tines have also been shown to increase significantly with speed (Stafford, 1979) but the relationship depends on soil and implement parameters.

Payne (1956), however, observed that draught force is not affected by speed. His speed range was 0.2 to 2.7 m/s.

Based on the review of past investigations, a considerable amount of work has been done on the soil mechanics associated with many basic cultivation operations. The majority of the studies, however, have been conducted at moisture contents below the lower plastic limit, exceptions to this are the works of Stafford (1979), Wismer and Luth (1970), Rajaram (1987) and Owen (1988) who worked in cohesive soils with moisture contents slightly above the lower plastic limit. All assessed both forces and the mode of soil failure except Wismer and Luth (1972) who confined their work to forces. Speed effects were considered by Stafford (1979) and Rajaram (1987) and Stafford (1979) also varied moisture content. Current soil implement mechanics theories have also been tested largely on soils at friable consistencies or near the lower plastic limit where mainly brittle failure occurred. Very few studies have tested their force predictions in plastic soils or investigated plastic failure patterns in conditions suitable for wetland cultivation.

2.2.2 Soil Failure by Multiple Tines

2.2.2.1 Work on Lateral Interaction

One of the earliest reports on lateral interaction refers to the work conducted by Rathje (1932) on two 15 mm wide tines varying in their spacing. The main finding was the dependence of the draught force on the ratio of the distance between the tines to the working depth. Later Zelenin (1950) studied the interaction of neighbouring tools on draught forces.

Working with two vertical tines 7 mm wide, he determined four different situations. The first situation was close spacing the two tines being from 0 to 20-30 mm apart, where there was complete interaction and the soil did not flow between the tines. The draught, however, increased with the spacing. By spacing the tines between 50 to 100 mm, the force decreased sharply. For the third spacing, between 100 and 300 mm, the soil was not completely broken up and the two distinct upheaval areas were found, while the draught force increased gradually. For wider spacings, there was no interaction and the draught force remained constant. Ferguson (1970) claimed a reduction in draught when measuring the draught forces on several combinations of 203.2 mm wide scarifiers shares on dry uncultivated sandy loam soil at 100 mm working depth. Soil bin studies carried by Chisholm et al. (1970) reported the possibility of large reductions of energy requirements for tilling the soil due to interference between two or more tillage tools. In 1975 Harvey as cited by Soomro (1976) constructed soil bin experiments to compare blade and tine type shares from the point of view of draught and soil disturbance. He concluded that tine interaction in a multiple tine share arrangement can reduce draught below that of a blade share with an increase in soil disturbance.

2.2.2.2 Shallow and Deep Tines Interaction

Spoor (1969; 1975; and 1976) described the pattern of soil disturbance with deep working tines. Above a certain depth, the soil moves upwards and he suggested that this depth can be increased if the surface soil layers are loosened before a deep cultivation operation. This can be achieved by placing shallow tines ahead of the deep tines. Spoor and Godwin (1978) experimental results reaffirmed the effect of shallow tines ahead of deep tines by causing a significant increase in disturbed soil without increase in draught. They introduced the concept of specific soil resistance expressed as the relationship between the draught force and the area of soil disturbance as an index of the efficiency of the tillage operation.

2.2.2.3 Combined Interaction

The effect of tine arrangement on soil forces and disturbance was studied by Soomro (1976). A narrow tine of 25.4 mm width raked at 45^0 was used at 68 mm and 150 mm depths in a sandy loam soil. His results revealed that:

a) Leading shallow tines in front of a deep tine effectively increased the soil disturbance for the same draught as the deep tine alone, so increasing the efficiency of work.

b) Leading shallow tines working at half the depth of the trailing deep tine were efficient when spaced at between 1 and 1.5 times the working depth of the deep tine.

c) Winged tines with leading shallow tines were more efficient than plane interacting tines.

Spoor and Godwin (1978) conducted an investigation into the deep loosening of soil by rigid tines. Tine performance was assessed in terms of the cross-sectional area of soil disturbed, the draught and the specific resistance. The investigation was carried out in both field and laboratory under a range of different soil textures, densities and moisture contents. They concluded that a critical working depth existed below which compaction occurred. This critical depth was dependent upon width, inclination and lift height of the tine foot and on the moisture and density status of the soil. The effects of attaching wings to the tine foot and the use of shallow leading tines to loosen the surface layers ahead of the deep tine increased soil disturbance, particularly at depth, reduced specific resistance, increased the critical depth and allowed more effective soil rearrangement. Complete soil loosening at depth and smooth soil surfaces could be achieved by selecting an appropriate tine spacing, which can be increased through the use of wings and shallow leading tines.

Evans et al. (1984) conducted a study on tool arrangement effects on draught force using a simple vertical chisel with a side relief angle of 39^0 and a width of 76 mm in two soil types, sandy loam and clay loam. A maximum depth of 229 mm was chosen. In clay loam, the specific draught forces were high at low aspect ratio values and then declined until they reached a minimum or levelled off at an aspect ratio of 1.5. This indicates the possibility of an optimum working depth for this system of tools. When tools were close together, the draught was lower but the area of disturbed soil was smaller. When two tillage tools were placed in front of, and on either side of, a third tool and were close enough to cause interaction between the outside tools and the middle tool, the total draught force for the system decreased.

The above studies on soil failure by multiple tines were conducted again at moisture contents below the lower plastic limit. No experimental evidence was found on studies conducted at moisture content above the lower plastic limit.

2.3 Wetland Tillage for Paddy Cultivation

2.3.1 Soil Condition for Rice Growth

Bates (1957) classified wet paddy land into three types, namely the clays, where a relatively firm bottom or pan exists beneath the surface, the silts and sandy silts which are often hardbaked in the dry season and become waterlogged in the wet season and the peats which have no firm bottom. According to Kawaguchi and Kyuma (1977) Moomaw and Curfs (1971); Van Dijk (1971) and Grist (1964), the most suitable soils for growing rice are clayey. However, with ample supply of water any type of soil can be taken up for rice growing. Impermeable soils are preferred as percolation losses in permeable soils render paddy cultivation uneconomical. Heavier soils have advantages over sandy ones because they retain nutrients better (Jamil, 1966). Other types of soils recommended are sandy loam and heavy silt loam (Richharia and Pradhan, 1966), and silt loam or sandy textured clay (Izumi, 1966).

Presently little quantitative data are available to fully describe the final soil state desired for successful rice growth in terms of structural requirements. Nevertheless, the required conditions have been defined qualitatively as a semi-pervious hardpan, covered with a relatively dense mud in which the organic matter is incorporated near the bottom. This seems most favourable for paddy seed germination,transplanting and root development (Grist, 1938). According to Van der Goor (1950), mud of a well prepared rice field contains considerably more moisture than the supersaturated soil clod.The necessity of covering with water is explained by the beneficial influence it has on the suppression of weeds and the low draught required to work the soil. The necessity of converting the soil aggregates into mud has usually been founded on the decrease of water loss it induces. It is also reported that mud helps increase the crop yield (Pandya, 1962).

Studies on the yield of rice by Van de Goor (1950) confirms the above finding. It was reported that the yields of the dry cultivated soils are lower than those of the wet cultivated ones, the difference being largest for the unweeded fields. This is due to better water uptake and less restriction to root growth achieved in mud compared to loose packing caused by granulation. When loosely packed, the exchange of ions between clay and soil solution is hampered so that only the outside surface is available for the exchange reactions and the root hairs are unable to penetrate into the granules. In the mud, the distance between the clay particles is large, compared to that of the granulated soil, so that the exchange reaction from the clay surface with the root hairs and the solution are less impeded. If the nutrient status of the soil is low, the reduction of the available surface by granulation might be the cause of the lower yield of the dry tilled soil compared to that of the wet tilled (Koenigs, 1961).

Kar et al. (1976) studied the effect of soil physical environments on growth and yield of the high yielding varieties under controlled conditions. The findings reveal that the rice plant is very sensitive to soil moisture stress. Temporary wilting has been observed below field capacity and growth is affected as soil moisture is reduced to field capacity. Rice needs no oxygen supply to roots through soil and the optimum soil temperature range is 25^0-37^0C. The majority of the rice root system does not go deeper than 8 - 13 cm even in a very loosely packed soil under flooded condition. Rice growth is favourably influenced by high soil density. A critical wet bulk density of 1.4, 1.6 and 1.8 Mg/m^3 was found to affect root growth in clay, loam and sandy loam soils respectively. Rice roots, however, can penetrate into extremely dense soil provided the soil strength is kept low by keeping the soil fully saturated.

According to Ghildyal (1969), it is the land submergence that provides some of the desired physical and nutrient requirements of rice plants. In Japan, Matsubayashi (1963) indicated that only 30% as many weeds emerged in submerged plots as compared with saturated ones. With increasing submergence depth, weed emergence is greatly reduced.

2.3.2 Tillage Operations for Rice Crop

Most rice growing countries employ two main systems for producing rice, the dry system (often referred to as upland rice cultivation and the wet system (often referred to as lowland rice cultivation). The advantages and disadvantages of wetland and dryland cultivation have been enumerated by De Datta et al. (1979). Among the advantages of the wet system are reduced tractive power requirement, improved weed control and minimization of leaching and thus of water loss. The disadvantages include delay in transplanting, poor condition for root development due to the formation of a plough pan and the formation of various toxic substances due to the creation of reduction conditions. Though dryland cultivation creates better prospect for earlier tillage due to mechanisation and better root development of the rice plant, weed control is more difficult and it demands better water control.

In the wet system, the land is flooded and the crop grown in wet soils from the time of seeding or transplanting until harvest approaches. Three water control systems are used depending upon the irrigation practices and the degree of water control achievable. These are:

a) continuous flooding during initial tillage, puddling, levelling and seeding or transplanting and water drained just prior to harvesting,

b) the initial tillage operations are performed before flooding after which puddling, levelling and seeding or transplanting are done at varying water levels, and

c) the land is prepared and the seed sown under dry conditions and then the field is flooded.

The most frequently employed is the first system. This type of tillage leads to the formation of a condition favourable for transplanting and growth of seedlings besides destroying weeds and rice stubbles and incorporating them into the soil. Simultaneously, the porosity in the subsoil is reduced, thereby forming a less permeable layer and considerably reducing percolation losses. This condition also is said to aid in the availability of nutrients particularly phosphorus due to closer contact between the soil and the rice root hairs. The depth of tillage varies from 10 - 20 cm. This provides sufficient loose soil for the later formation of a satisfactory puddle. If the depth of of tillage is less than 10 cm, weed control in the later stages will be inadequate. Depths greater than 20 cm can result in decreased yields. This is due to the fact that organic matter becomes buried too deeply for the root systems to reach the plant nutrients.

The first stage in the tillage operation is frequently the plastering of the inner surface of the bunds either by hand or by turning a single furrow just inside the field with a plough. The top soil is made finer, stirred and moved. This is accomplished by a cutaway disc or turning plough which breaks large furrows and incorporate organic matter. Later this is followed by a comb harrow and frequently by a levelling board to prepare a smooth even puddle to the required depth. When a tractor is used, the rotary cultivator is frequently the only implement attached. This is occasionally followed by a harrow and levelling board depending on the nature of the soil. The hardpan layer is further compacted by working men or animals or by wheels of a puddling machine. In heavy clay soils this hardpan layer may not occur. Such soils, however, are not of a porous nature and therefore a hardpan layer is not necessary for conservation of water and plant nutrients. In soils which are poorly drained throughout the whole year, a hardpan layer may not be desirable and it may be necessary to break it up.

Following primary tillage, at least two stages of puddling are required for maximum production of rice. After the first puddling operation, the water is usually left on the field for seven to ten days and then drained for final puddling. In the puddling stages, several factors help to build a hardpan layer on the bottom of the puddle. Fine clay particles work down into the porous parts of any previous hardpan. The flooding period used between puddling stages is known to assist anaerobic decomposition of organic material in the lower part of the mud layer. The performance of the successive operations through primary tillage, first stage puddling and flooding and last stage puddling gives more effective weed control. This procedure brings fresh soil to the surface several times and therefore more weeds can be expected to germinate and be destroyed. Stout (1966) reported that weeds can be killed and trash buried more economically in the puddling operations than by inversion, since soil inversion and weed killing in the primary tillage operation requires large amounts of water and increases the time required for final operation. Results of Matsubayashi as reported by Stout (1966) indicate that soil inversion is not necessary.

Fagi and De Datta (1983) demonstrated that the optimum soil moisture content for ease of tillage varied with soil types. In silty clay soil, a wide range of moisture contents for ease of tillage was observed and was not influenced by the cropping system and crop residue management. Soil impedance was found to increase as soil moisture content increased, until the moisture content reached 57% where the soil was very sticky. Further increases in soil moisture content decreased soil impedance. This means that the time span for ploughing after the field becomes moist is wide in silty clay soil. To puddle this type of soil, the field should be ploughed in that moisture range, or delayed until the field impounds enough water for the soil to become sticky.

In sandy clay loam, soil impedance dropped drastically from about 4.5 to 1.75 kg/cm^2 as soil moisture content increased from about 25% to 32.5%. It decreased slightly as soil moisture content increased beyond 32.5%. The narrow range of soil moisture content within the shrinkage limit and plastic limit of the sandy clay loam soil implies that the fields should be ploughed as soon as they become moist. The good drainage and lower moisture retention capacity of this soil causes the fields to dry easily, aggravating the process of hardening. Therefore puddling sandy clay loams is too risky under rainfed conditions. Incorporation of crop residues is recommended for sandy clay loam soils to improve soil moisture retention and to reduce soil moisture stress.

The tillage operation varies from country to country (FAO, 1956). A number of examples are given. In Bangladesh, land preparation is accomplished by a bullock drawn beam country plough which is light enough to be carried on the shoulder. Its action is more like a one tined cultivator or chisel than a plough and it shears the soil without inversion. About three to seven ploughings are necessary to break up the soil completely. To prepare an acre of land takes from nine to twenty-one days and requires the cultivator and bullock to cover more than 160 km. After ploughing, the seedbed is usually left in large clods. A ladder harrow made of bamboo with one or two men standing on it is pulled over the land by one or two pairs of bullocks to break the clods. A similar system is practised in India where the land is ploughed six to eight times. In the Republic of China, land is ploughed several times with the aid of buffalo drawn ploughs although sometimes two ploughings are sufficient. Buffaloes are being successfully replaced by small 3 hp motors. Each ploughing is 12 to 18 cm deep. Harrowing is done lengthwise and breadthwise in the field, followed by levelling.

In the Philippines, irrigation is applied a week prior to the preparation of land to facilitate ploughing. The depth of water is just sufficient to soften the soil and prevent the soil from sticking to the plough. After ploughing, more water is added to expedite the decomposition of weeds and crop residue which are ploughed under. To prevent loss of nitrogen due to denitrification, seven to ten days after the first ploughing, flooding is maintained until transplanting. The depth of standing water may be lowered after this period, when the field may be harrowed lengthwise and crosswise. Again after seven to ten days there may be second lengthwise and crosswise harrowing.The last harrowing is done a week after the second harrowing, or at least a day before planting, to puddle and level the field thoroughly.

In Sri Lanka, wooden ploughs have proved effective for wet cultivation. After ploughing operations, the field is drained overnight leaving about 7.5 cm of water. A tooth harrow, yoked to a pair of buffaloes or cattle, is then drawn over the field returning over the same strip in the opposite direction. This operation is then repeated in the crosswise direction. Overall the harrow is drawn over the entire field four times. It is stated that 1.13 to 1.62 hectares can be prepared in a day.

In Burma, cattle are usually employed for ploughing. Rates of working for a pair of cattle per day of six hours are 0.135 ha for ploughing and half a hectare with a blade harrow.

For puddling a rotating blade puddling implement is in common use. This is a drum type equipment for which two draft animals are required to pull a 180 cm wide drum. Puddling may also be done by tractors with 5 to 6 cm of standing water in the field. The wet field is ploughed repeatedly four to six times at four or five days intervals, followed by planking for levelling. Soils are of tertiary sediment and alluvium, the soil texture being fine. Lately Japanese power tillers have proved acceptable because they are light in weight, compact, easy to operate, cheap, have great manoeuvrability in small fields and are able to perform other kinds of work around the farm. The 2.5 hp machine is considered suitable for light soil, 3.5 hp for heavy soil and 5 hp for farms wishing to use them for other jobs requiring greater power.

The power tiller is popular in Japan. The depth of ploughing is generally 10 to 15 cm which may go up to 20 cm or more in the case of four wheeled tractor drawn ploughs. The soil in the field may be ploughed with a moldboard plough and worked down and puddled with a disc or comb harrow. The labour requirements for ploughing and puddling are 100.4 hr/ha and 67.8 hr/ha respectively.

In Korea, livestock and farm machinery are used for ploughing, harrowing and puddling. Cows are found to be more effective in hilly and sloping lands while farm mechanisation is on the increase in broad flat land.

Rice production in the United States of America is characterised by a high degree of mechanisation and precise water control. The land is ploughed with large tractor drawn moldboard or disc ploughs. When rice is seeded on clay or very fine loam soil, the preparation of the seeded is undertaken by harrowing twice with a spiked tooth harrow followed by levelling.

In Malaysia, disc harrows have been found to be successful in wetland cultivation. Light disc harrows break down clods in dry or flooded fields but they are useless when the land is merely wet. Another successful implement designed locally is the Kedah roller. It is constructed of steel having a width of 1.5 m and an overall diameter of 0.3 m and weighs 215 kg with two rolls or 146 kg with the rear roll removed. This double roller has recently been superseeded by a 25 cm diameter roller which is said to be better in most cases than the drum roller devised for deep and very wet land. The drum roller consists of 200 litre fuel drums mounted end to end on a long shaft and fitted longitudinally with wooden slats 7.5 cm high. The whole is mounted on a light steel frame and directly attached to the hydraulic power lift. The weight can be varied by filling with water through screw-on caps. Lately these rollers have been replaced by the imported Japanese rice rollers as mechanisation progresses intensively in all operations (UMAS, 1982).

Clearly from the above review, the most frequently employed method in wetland rice cultivation is continuous flooding during initial tillage, puddling, levelling and transplanting with water drained just prior to harvesting. This method helps reduce weeds and reduces soil strength for root growth. The time span for puddling silty clay soil is wider than for sandy clay loams since good drainage and the lower moisture retention capacity of the sandy clay loams causes the fields to dry quickly. The majority of the rice growing countries still employed animals as the source of power to plough the land with the traditional plough. Disc harrows and rotating puddlers are employed in the puddling operation. The energy and time requirements are high to churn the soil into the required condition. Where power resources are not limited, fields are prepared quickly with the use of rotary cultivators.

2.3.3 Soil Factors Influencing the Efficiency of Puddling

Throne and Peterson (1950) defined puddling as a process in which soil lost granular structure and became deflocculated. This state could be measured by wet sieving and determining the mean weight diameter according to the method recommended by van Bavel (1950). According to Lyon et al., (1952), when a clayey soil is worked, its pore spaces are much reduced and it becomes practically impervious. In such a puddled state, the colloidal material is a controlling factor. These effects are measured by determining the specific weights and moisture contents of the puddled soils. Bodman and Rubin (1948) defined puddling as the reduction in the apparent specific volume (reciprocal of bulk density) of a soil by doing mechanical work on it. Two kinds of soil deforming processes, namely compression and shear were observed to cause puddling. They developed equations to show how the change in volume per unit work was related to the air filled pore space. They also suggested the term 'puddlability' to mean the change in apparent specific volume of soil per unit of work expended in causing such a change. Sharma and De Datta (1984) reported that compression is most effective below the upper plastic limit while shearing effects dominate above the upper plastic limit.

One of the critical factors controlling the degree of puddling is moisture. The detailed studies of Mc George (1937), Mc George and Breazeale (1938), Bodman and Rubin (1948), Beacher and Strickling (1955) and Baver (1956) demonstrated that a maximum state of puddling was attained at a moisture content closely approximating the moisture equivalent (pF 2.7) beyond which puddling decreases. The only mechanical effect noted on working with an excess of water was a dispersion or breakdown of the crumb structure. Field soil that is prepared by dryland tillage will always produce clods. For effective puddling after this it is important that the maximum energy applied be transferred to the clods. This is possible only when the clods do not move easily over each other and along the implement. At low moisture content, cohesion between the aggregates and clods is a maximum and movement of aggregates along each other and along the implement is therefore restricted. According to Koenigs (1963), cohesion between clods and the adhesion between the clods and the implement surface are mainly caused by a water film adhering to both surfaces. When studying the mechanism of soil adhesion, Fountaine (1954) found that it depends on the soil water suction at the interfaces of soil-soil or soil-metal and on the relative area of contact. At high suctions the number of water bridges is too small to cause sufficient adhesion. On the other hand, if the soil is saturated, the suction is too low. Thus a maximum of adhesion is found at intermediate suctions where it lies near a point either called the moisture equivalent or field capacity. Hence it is to be expected that the maximum puddling action will take place at suctions very close to this water content because a maximum of energy is transferred to the clods while the internal cohesion is considerably lower than in an air dry clods so shear planes may easily formed (Bodman and Rubin, 1948). In the field, puddling at the sticky point would be difficult to achieve since operation would be hampered by the stickiness of the soil and water is always needed to help scouring and hence reduces the draught requirement. According to Sharma and De Datta (1984), soils with high cohesion within aggregates caused by stabilizing agents need a larger energy input for puddling. High clay content favours puddling but kaolitic clays are more difficult to puddle than montmorillonite clays.

2.3.4 Measurement of Degree of Puddling

Methods for measuring the degree of puddling have been reported by a number of researchers. Taneja and Patnaik (1962) used a simple penetrometer to determine the effective depth of puddle by applying a force ranging from 1 - 9 kg/25 cm^2. Depths penetrated by the penetrometer were measured. To determine the degree of puddle based on the concept of the destruction of large pores and apparent shrinkage in specific volume of soil, they centrifuged samples of puddled soil at 2000 rev/min and measured the shrinkage depth as the degree of puddle.

Naphade and Ghidyal (1971) studied the physical properties of soil such as the aggregate distribution, apparent specific volume and hydraulic conductivity and related these to the degree of puddling, using a laboratory puddler and field rotary tiller. The puddler consisted of a variable stirrer with four blades fitted to the motor shaft which, while rotating, puddled the soil. The energy input expressed in watt-hours required produce the desired degree of puddling was measured.

Sinha (1963) developed an index of puddling based on soil particle dispersion calculated as the ratio of the volume of puddled soil after and before settling for about 48 hours. A higher value indicates a greater degree of puddling. Sharma and De Datta (1984) on the other hand suggested that for applications in rice research, one should use a combination of indices that characterise both softness (for ease of transplanting) and permeability to water (for economy of water and nutrients). A joint index of bulk density and percolation rate has been suggested as the most effective.

Pandey and Ojha (1971) defined a puddling index as follows:

$$PI = (Vs - Vc/Vs) \times 100 \quad ....(2.11)$$

where PI is the puddling index, Vs the volume of soil settled in the sample and Vc the volume of clear water. This relationship gives negative values of PI when the volume of soil settled in the sample is less than the volume of clear water. An improved expression was later determined according to the equation given as

$$PI = (Vs/V) \times 100 \quad ....(2.12)$$

where PI is the puddling index, Vs is the volume of settled soil in the sample and V the total volume of sample. This relationship holds good from zero puddling. The major drawback, however, is that the value of PI is dependent on the depth of water standing in the field.

Konaka (1974) studied the dynamic properties of puddled soil and measured them by resistance to cone penetration and falling cone depth. The cone index obtained by inserting a cone penetrometer is representative of the characteristics of puddled soil. The main drawback of this test is that it is difficult to conduct and the result cannot be shown as one value. To represent the dynamic properties of puddled soil, it was suggested that the mean and standard deviation of water depth, the pan depth and penetration depth of a falling cone should be measured. This is considered to be an excellent measure to predict the supporting force of soil for rice seedlings.

In an effort to measure the quality of puddle, Awadhwal (1985), examined the merits and demerits of shear strength parameters like yield shear strength, secant modulus, energy of deformation and rheological characteristics such as degree of plasticity, viscosity and parameters of a viscoelastic model, together with some other characteristics like relative density and hydraulic conductivity of puddled soil. The yield shear strength was found to be the most suitable basis for quantification of the state of puddle. The term "degree of puddle" was defined as

$$DP = 1 - Tp/Tup \qquad ....(2.13)$$

where DP is the degree of puddle, Tp the yield shear strength of puddled soil and Tup the yield shear strength of unpuddled soil.

2.3.5 Puddling Efficiency of Different Tillage Implements

Puddling implements vary in their performance and their efficiencies are often determined by the number of operations and hence the energy used. This is further determined by soil types and initial water depth. A study of puddling (Have, 1972) performed with an indigenous plough, moldboard plough, disc harrow, rotary cultivator and tractor with cage wheels shows that the rotary cultivator is most efficient in terms of reduction in percolation loss. The rotary blade puddler, rotary cultivator and power tiller perform better in terms of energy requirement, crop output and overall economy when compared with a cultivator, pedal type puddler and double cage wheels. The performance of double cage wheels as puddling equipment is poor and their depth of cultivation is comparatively low (Singh, 1961).

Richharia and Subhiah Pillai (1962) conducted some experiments with bullock power and mechanical power on three types of soil. Using bullock power, it usually required five to six ploughings with the standard plough conducted in three sets of operations with an interval of about four days between each set, with 5 to 8 cm of water to produce an ideal puddle for light loamy soils. Medium soils required six to eight ploughings, and heavy soils eight to ten ploughings. The average area covered in one hour (one ploughing) by a pair of bullocks was 0.06 to 0.86 acre. For the tractor experiments, a tractor with steel extension wheels fitted to standard pneumatic wheels and complete with a paddy disc harrow was used to disturb the field lengthwise and crosswise once, in 22 to 30 cm of water. After a lapse of one week, the tractor was again worked once or, twice depending on the state of the puddle obtained. For loamy, medium and heavy soils, the number of runs required was two, three and four respectively. The average area covered per run was 1.25 to 1.50 acres. No quantitative measurements were made.

Have (1967) describes the advantages and the disadvantages of some implements which consist of closed rollers with steel knives or iron strips attached to the circumference (parallel to the axis), open rollers, disc harrows and boards or beams. Closed rollers consist of three units 50 cm in diameter and 150 cm in length, and on whose circumference eight 13 cm wide knives were fitted. The degree of compaction and puddling depends on the weight, diameter and driving speed as well as spacing, breadth and thickness of the knives or strips. Sharp knives penetrate further into the soil and are better at cutting up the weeds, whereas strips bury them more effectively in the soil. In consequence of the large bearing surface, soil is hardly loosened. Open rollers are unfavourable in soft soils, whereas disc harrows can be regulated as regards the depth and intensity of operations. Disc harrows have a cutting action and exert little compacting force on the soil. Weed vegetation and straw residues can be well incorporated. Boards and beams on the other hand serve to level and smooth the seedbed and to cover the plant remains with a layer of mud. In principle they are only used for the final operation, whether or not in conjunction with another implement. The soil is compacted and levelled according to their dimensions and weight.

Dutt et al. (1986) worked on an animal drawn float harrow. The disc gang was hollow in the form of a drum and floated over the soil. It gave a higher output than conventional ploughs and disc harrows. The float harrow was tested on a field ploughed once by a moldboard plough. The harrow consists of two hollow drums of 35 cm diameter. Three disc blades of 60 cm diameter were mounted on each drum, and between the two gangs of disc, a cultivator tine was provided.

Nichols (1976) demonstrated that C-shaped blades (speed blade) of the rotary cultivator performed better than the L-shaped blade (power blade) in terms of tilth quality and shallowness of operation. The rotor speed required however was higher. Earlier experiments on the effect of blade shape by Khoo and Beeny (1970) showed that the power blade consumed the most power, but provided the biggest thrust. Tests were conducted in a supersaturated soil with 50 mm of standing water.

Koenigs (1963) compared the performance of puddling implements and concluded that the longer and more intensive the kneading action the better the puddling will be in the case of ploughing with rotary tillage. The range of moisture contents over which puddling may occur will be wider the more the clods are constrained (in the case of a wheel or roll compared with a plough). During the passage of a wheel or roll, the direction of the normal load changes continuously from forward to downward and backward. Therefore, the direction of the shear planes will also be changing continuously and , in this way, the weakest plane in the clods is found. This also explains the severe puddling caused by these implements at high moisture contents and their effectiveness in reducing the size of clods at lower moisture contents.

Agarwal et al. (1978) assessed several implements suitable for puddling by operating once or twice in sandy loam soil. The duration of the operation in reducing the percolation loss was noted. The implements used were a tractor with cage wheels and a disc harrow, a tractor with cage wheels and a rotary puddler, a Yanmar power tiller with cage wheels and a bullock driven indigenous plough followed by planking. The results obtained show that the indigenous plough, followed by the planking treatment, was far superior in reducing percolation loss compared to other implements when operated alone. A tractor with cage wheels and a rotary puddler was almost similar in its effect to a Yanmar power tiller while a tractor with cage wheels and a disc harrow was least effective in reducing the percolation losses in a single operation. Percolation losses were markedly reduced with a tractor with cage wheels and a harrow and with Yanmar power tiller with cage wheels when operated twice. A rotary puddler and indigenous plough on the other hand, did not caused any marked reduction in percolation loss when operated twice. Percentage silt plus clay dispersed by different implements was in agreement with that of percolation losses measured in the field. Considering the time required, and the effectiveness of implements for puddling, for smaller farm holdings, an indigenous plough and planking appears to be suitable practice, whereas for larger holdings and mechanised farming, a tractor with cage wheels and a harrow or a rotary puddler are suggested. Earlier work by Sinha (1963) on the performance of different implements concluded that modified T-shaped rotary type blades were the most efficient in terms of draught, output, depth and puddling index. Experiments were conducted in 10 cm standing water.

Tiwari and Bachchan Singh (1985) conducted a field study on the effect of blade angle, blade width and number of operations of tractor drawn rotary puddlers on puddling quality. Puddling quality was judged on the basis of puddling index, percolation loss, bulk density and hydraulic conductivity. On the basis of the above criteria, a 30^0 blade angle and 75 mm blade width were found to be the best for puddling.

Prihar et al. (1976) conducted a field study to determine the effect of conventional puddling, compaction and mechanical puddling on the percolation rates, the total water loss and the yield of paddy in a sandy loam soil. Whereas the yield was unaffected, the percolation rates and the total water loss differed considerably among the various treatments. From the standpoint of percolation losses, puddling with a disc harrow, angular puddler and rotovator was either equal to or better than that with a traditional plough. Compaction did not show much promise as a substitute for puddling.

Awadhwal (1980) presented a method for comparing the performance of two puddling machines by accounting for the specific energy spent in puddling and measuring the shear strength ratios of puddled soil. The term 'performance ratio' was defined as the ratio of the efficiencies of the puddling equipment. It was proved that performance ratio can be expressed as:

$$E1/E2 = (J2/J1)x(\ln(Tr1)/\ln(Tr2)) \quad .....(2.14)$$

where

E = efficiency of puddler

J = specific energy

Tr = ratio of vane shear strength of puddled soil to vane shear strength of unpuddled soil. Subscripts 1 and 2 indicate puddling equipment 1 and 2.

The above review indicates that puddling implements vary in their performance in reducing percolation loss depending on soil type, water depth, number of operations and power availability. Where power resources are limited, puddling is done with the help of animals. The animal drawn implements consist of an indigenous plough, a moldboard plough and a comb harrow. The traditional plough normally has a relatively wide cutting face with a steep rake angle and a flat bottom. It cuts off weeds more effectively and tends to form a better plough sole. Most indigenous ploughs do not invert and so do not disturb field levels by leaving high crowns and deep dead furrows as may be the case with a moldboard plough. The moldboard plough inverts the soil but is heavier in draught and tends to disturb land levels. The comb harrow, on the other hand, helps break clods, press the organic matter downwards and churn the soil after a few passes. Its draught is relatively heavy and difficult to operate at an even depth. The use of rollers has also found increasing favour. Metal strips and blades are welded to the roller and these strips help cut and bury weeds. Rollers break clods and require less draught to produce a satisfactory puddle. All the implements require two to four passes to produce a satisfactory puddle depending on soil types and need standing water on the surface.

The puddling implements used with a four wheeled tractor are tine tillers, rotating blade puddler, disc harrow and rotary cultivator. Tine tillers need free water on the surface to reduce trash clogging. They do not invert the soil and do not compact the soil as much as the plough. More passes are needed to disperse soil particles. The rotating puddler, on the other hand, is lighter but needs water in the field. T-shaped blades have been recommended for effective puddling. Disc harrows have a cutting action and exert little compacting force on the soil. Deep concavity increases the draught requirement and the amount of soil inversion. More passes are required in heavy soils to disperse soil particles. The rotary cultivator is fast becoming popular as it tends to invert the soil and chops and buries trash simultaneously. It requires no drawbar power and produces fine degree of pulverisation, enabling the necessary rapid and intimate mixing of soil and water resulting in the favourable mud puddle for the growth of rice seedling. C-shaped blades perform better in terms of tilth quality compared to L-shaped blades. The rotary cultivator needs only one or two passes and is most effective when used with cagewheels. Cagewheels increase the area of soil subjected to shear and serve as a puddling tool. However, its performance is poor when operated alone and the depth of puddling is low. Apart from using implements, animals are also used to trample the field after primary tillage once the fields have been completely flooded. When the trampling is completed, the organic matter will be at the bottom and the water is mixed with the soil forming a slurry of thick mud on the surface. If an indigenous plough is used, it merely stirs the soil and loosens the root systems and the animals trample them down to the hardpan layer. For effective puddling either more animals or more passes are required.

2.3.6 Water and Energy Requirement in Tillage Operations

The first operation that prevails in an irrigated system cropping schedule is land preparation, and at this stage, the demand for irrigation water is at its peak. According to Wickham (1972), the amount of water supplied during land preparation is often more than one third of the total supply in growing a rice crop. A similar finding was reported by De Datta (1981). IRRI data show that the water required for puddling the wetland field was about 150 mm. Water use in non-puddled field was only 50% of that used in the wetland field, despite the much longer duration of the non-puddled planting (De Datta et. al, 1973). The average daily rate of water use in the puddled field was 7.71 mm/day. For the non-puddled field, the daily water use was 3.37 mm/day. An average over the whole growing season for the water use of the non-puddled field was 44% of that of the puddled field. Earlier work by Kumar et al (1977) indicates that the water requirement for land preparation on deep clay loam soils in the absence of high water table appears to vary from 13.6 to 30.5 mm. Below this level, the consistency of soil water system was not satisfactory for the puddling operation. The soil was more sticky and water was insufficient. Above this value also resulted in insufficient puddling due to excess water.

Sarker et al. (1985) conducted a study on total water requirements for land preparation and land soaking and reported that:

a) Land soaking and land preparation required about 15%-20% of the total water supply in growing transplanted rice, depending on soil types and topography. Fields ploughed before irrigation were found to have saved 50% of the water needed for land soaking and land preparation. This indicates that pre-irrigation tillage practices are advantageous in terms of reduced water demand and resource utilisation. Pre-irrigation tillage also requires fewer post irrigation operations and utilises residual soil moisture available after the wet season.

b) Higher yields of rice were obtained on all the plots where pre-irrigation tillage was practised.

c) Cost of land preparation was found to be lower where pre-irrigation tillage operations were limited to three and post irrigation ploughing operations to one. Increasing the pre-irrigation operations beyond optimum numbers did not show any significant variation in cost for tillage operations for the two practices.

Painuli et al (1988) investigated the effect of reducing water and energy on puddling using different type of puddling implements and machines in soils of low bearing strength. Intensive field studies showed that effective puddling (defined and measured as the resulting decrease in the rice season's total vertical percolation of water) can be achieved with inputs both of land soaking water and of soil working energy that are less than those traditionally used. Results showed that saving water by decreasing the season's total percolation from 3000 to 120 mm could be achieved without any concurrent penalty of grain yield.

The amount of water use for land preparation and initial flooding varies from country to country. According to Kung and Atthayodhin (1968), 200 mm of water is commonly used for land preparation. Table 2.2 shows water use for land preparation and initial flooding in various Asian countries.

In Malaysia, estimates of the water requirement for saturation and land preparation for a lowland puddled field are 505 mm for the wet season and 570 mm for the dry season. In India, out of the total water supplied for rice production, as much as 75% is lost due to poor soil and water management practices through deep percolation during land submergence (Vamadevan and Dastane, 1968; and Yadav, 1972). Excess water is not only a waste but also creates trafficability problems. The effect of water management on penetrating resistance of rice soil has been well described by Subbaiah et al. (1984). They recommended that the soil strength should not be less than $20 N/cm^2$ to enable a machine to be driven without sinking.

Energy requirements in rice cultivation have also been of a major concern in recent years because of escalating costs of fuel and other agricultural inputs. When rice is grown following dry soil preparation, the major drawback is the high power requirement when compared with operations in wet soils. On heavy to medium textured soils, the power has been shown to be substantially greater under dry conditions than when saturated. The tillage labour requirements have been analysed by several authors namely Johnson (1963), Stout (1966), Sakan Komori (1974) and Kuether and Duff (1981). Data compiled by Johnson (1963) indicates that when mechanical methods are compared in terms of rated horsepower-hour per hectare, the differences between man, animal and machines are not so evident, owing to the high variation between working depth, soils and the tests carried out

(Table 2.3). Kuether and Duff (1981) on the other hand analysed the energy requirements of three production systems consisting of traditional (entirely human labour and animal power), mechanical (tillage with power tiller) and transitional (primary tillage with a tractor). The use of tractors in the transitional system increased the total energy input by 5% but served a useful function in reducing considerably the time required for land preparation activities.

According to FAO report (1956), the average primary tillage with man powered tools may require 80 hours or more per acre. In Sri Lanka, ploughing with a country plough takes about 25 hours per acre while in Thailand and Japan, ploughing takes 20 and 16 hours respectively. The country plough may need cross ploughing at least once, which would double the energy requirements. Case studies of walking tractors from Japan and India have shown that ploughing dry fields requires 4.4 to 7.4 hours per acre and harrowing dry fields takes 2 to 4.6 hours per acre.

The above review suggests that considerable amount of water could be saved if pre-irrigation tillage is practised where only residual moisture content is used for land ploughing. Pre-irrigation tillage also requires fewer post irrigation operations and hence reduces the energy requirement. Land submergence is absent and hence overcome trafficability problem. Where animals are the source of power, longer period is required to prepare the land. Timeliness of operation could be achieved with implements that cover bigger area and prepare land quickly.

In conclusion, despite the numerous work conducted on soil puddling, no information is available on optimum water level and the most efficient implement that creates the required condition. Implements tested were suited to specific requirements for a specific soil type with very little work done to relate the resulting condition to rice root requirement. Nevertheless, puddling was aimed at reducing percolation loss and this could be reduced by dispersing more soil particles by increasing the number of passes in case of draught implements or operating powered implements at a greater speed depending on water level and soil type. Light soils require shorter duration to disperse while heavy soils require longer duration due to their cohesive nature. Implements that could disperse soil particles as quickly as possible would be the ideal choice and apparently justify the popularity of the rotary cultivator where power resources are not limited. The rotating puddler seems to be the best choice where animals are still the prime mover. The adaptability of the rolling tillage implements is worthy of further investigation since they tend to compact the subsoil, chop and press down organic matter and have relatively low draught. Comparative performance between implements has been suggested based on shear strength of puddled and unpuddled soils measured by a shear vane and the specific energy input consumed by implements.

CHAPTER 3.0 RESEARCH METHODOLOGY

In order to obtain some understanding on the behaviour of soil at high moisture content and to explore the potential for preparing paddy fields with reduced amounts of water, three laboratory experiments were conducted.

The first study was on the rate of water uptake by clods of different sizes and at different initial moisture contents. As the aim of the project was to use less water by avoiding complete submergence, wetting was done by capillarity. Clods were prepared by remoulding wet soil and formed into cubes for easy contact with the wet surface of a water conducting material. In order to arrive at different initial moisture contents, clods were exposed to a constant flow of hot air at 25^{0}C. Field clods were initially proposed, however, the idea was dropped for a number of reasons. The prime reason was the great variability between field clods and hence the large number of clods for testing that would have been required. The other drawback of field clods is the non-uniformity of moisture content. The moisture gradients within a clod too vary from one clod to another and it would take a longer time to dry them to a constant moisture content. Attempts were made to cut square block of field soil with a cheese wire, but it had to be abandoned since the soil crumbled apart easily. The alternative way was to destroy the structure and prepare clods from remoulded samples.

Two experimental treatments consisting of clod wetting and clod drying were tested. For treatment on clod wetting, three sizes of clods were prepared from different initial moisture contents. Duration of wetting was 7 days. A pilot study taken for

40 days showed that the change in moisture content beyond 7 days was not significant. The treatment on clod drying involved only one initial moisture content where the soil was fully saturated. Three clod sizes were prepared and the duration of drying was varied from 4 to 120 hours at 25^0 C . For each clod size three replicates were tested.

Prepared samples exposed to drying and wetting, were examined by slicing every 5 mm thickness from the base. Results between clod sizes were compared and the rate of water uptake or loss determined. This would give some indication of the effect of clod size and its initial moisture content on the rate of water absorption. This information is vital for timeliness of land preparation in areas where water is scarce and time for land preparation is short. These results would also indicate whether wet clods should be left undisturbed as big clods or broken into smaller aggregates.

During primary tillage, clods are normally formed in various sizes. The effect of wetting by capillarity would certainly be different for subsurface and surface clods. To explore this difference, experiments were conducted under two conditions, confined and unconfined. Confined clods representing those from the subsurface layer which would be confined by the clods above, were prepared by exerting loads on samples during wetting. The effect of soil layer, clod size and duration of wetting on moisture content was determined.

Results from the above experiments were tested against infiltration models based on linear flow of heat into a solid

(Carslaw and Jaeger, 1959) and that of Jarvis and Leeds-Harrison (1987). The earlier model was aimed at predicting the saturation state of each soil layer within a clod for different wetting period whilst the lateral sorption model of Jarvis and Leeds-Harrison was used to predict the height of water infiltration into soil cubes. Where input parameters were difficult to measure, empirical equations were used.

A second project involved the study of soil deformation at high moisture contents. Experiments were conducted in the plastic moisture range using simple tines operating at various rake angles and depths in a soil tank. A laboratory study was adopted because of the ease of controlling moisture content and the absence of weather effect as would be experienced normally in the field. The principal objective of the study was to utilise soil implement mechanics knowledge to improve the efficiency of soil preparation for wetland crops. Aspects like the nature of disturbance, extent of disturbance and draught requirement were investigated. It was anticipated that the results would reveal the optimum range of moisture contents at which tillage should be conducted to achieve the required disturbance and for a given condition, the most efficient type of implement which should be recommended.

Experiments were conducted with both single and multiple tines. For the single tine experiments, plane relieved tines ranging in widths from 25.4 mm to 152.4 mm were operated at three depths from 50.8 to 152.4 mm and at three rake angles varying from 450 to 1350. Tests were conducted in a cohesive soil at 42%, 56% and 70% moisture contents (dry basis). At 70% moisture content, tines greater than 50.8 mm width were set only at two depths because of the limitation in power supply from the motor. At 42% and 56% moisture contents, only narrow tines below 50.8 mm were investigated. A 3x2x3 factorial experiments were conducted for the single tines with each treatment replicated three times for the three moisture contents tested. An additional 4x2x3 factorial experiment was conducted at 70% moisture content to determine the effect of tine width on soil disturbance and tine forces. A three-way analysis of variance was carried out on all results using an ANOVA package.

The performance of multiple tines, each of 25.4 mm width and acting vertically, was assessed at 56% and 70% moisture contents. The test at 42% was not possible due to power limitation whilst the use of forward and backward inclined tines was restricted by the space between the carriage rails and the top of the soil tank. Three tines were used with two leading tines operating at 50.8 and 101.6 mm depths. The depth of rear tine was fixed at 101.6 mm while the longitudinal distance between the leading and the trailing tines was kept at 203.2 mm apart. Three tine spacings were investigated and for each spacing, the experiment was conducted three times. Results were subjected to one-way analysis of variance for the two moisture contents tested.

Prediction models based upon Mohr Coulomb soil mechanics theory were developed to predict the interaction between soil and simple implements used in the study based on soil disturbance pattern. The trajectory of the soil particles was monitored by soil movement detectors in the shape of coloured plastic beads implanted in a regular grid in the path of the tine. The movements were measured before and after the passage of each tine. A glass sided tank experiment was also conducted to support the bead tracer technique in observing soil deformation.

The third project was an investigation into the effect of water quantity on the degree of puddling using air dried aggregates. The work was confined to a laboratory study since it would be difficult to control water level in the field and would require a separate detailed study altogether, which was beyond the scope of the whole project in view of the limited time available. The aim of the fundamental study was to determine the property of a puddled soil in terms of its wet bulk density and aggregate size distribution. These were then compared to the optimum conditions for rice root growth as found in the literature. Soil puddling was carried out using a rotary puddler to simulate the rotary motion of the rotary cultivator normally used in the field. The puddler was driven by an electric motor with a variable speed controller. The literature review indicated that the rotary cultivator was found to be a good implement as it disperses soil particles quickly and requires negative draught force.

Four water-soil ratios were selected varying from 0.8 to 1.4. Measured quantities of water were added to 400 grams of air dry aggregates (8.7% moisture content) to arrive at the required water-soil ratio for puddling operations. Three stirring times of 5, 10 and 20 seconds were adopted to represent the the effect of different puddling energy inputs achievable using different types of puddling equipment. In ideal situations, a single pass would take less than a second to churn the soil. However, in the laboratory study, longer durations were adopted since it was difficult to obtain the results in one second. All tests were conducted at a steady motor speed of 2000 rev/min. Three replicates were used for each water-soil ratio tested. All results were subjected to two-way analysis of variance using the Anova package. Experimental treatments and the assessments made for all the above studies are summarised in Table 3.1 whilst Table 3.2 shows the detailed treatments for each experiment conducted.

CHAPTER 4.0 EXPERIMENTAL TECHNIQUES AND APPARATUS

4.1 Determination of Soil Physical and Mechanical Properties

The following soil properties were determined to quantify and classify the soils and conditions used in the different tests. The soil properties measured were soil texture, plastic and liquid limits, moisture retention characteristics, soil shear strength and soil-metal sliding shearing resistance.

The particle size distribution was determined by the pipette method as described by Day (1965) with organic matter destroyed during the pretreatment procedure by digesting with hydrogen peroxide. Organic matter content was determined on separate subsamples by dichromate oxidation.

To determine the plastic limit, air dry soil was sprayed with distilled water until it became plastic and kneaded to break down any structure and to ensure that the mass was all at the same moisture content. Once the mass became homogeneous and plastic, a portion of the soil was shaped into a ball and rolled out on a glass plate between the fingers until a wire 3 mm diameter was formed. This procedure was repeated until the 3 mm diameter soil wires broke into pieces about 6 - 12 mm in length. The moisture content of some of the broken pieces was determined and expressed as a percentage of the oven dry soil.

The liquid limit was determined by using the Casagrande apparatus (Head, 1980) and a cone penetrometer. Moisture retention characteristics were determined by the pressure membrane technique as described by Richards (1947).

In this study, the triaxial test was chosen to measure the soil shear strength because it is the most controlled method and has been used by numerous authors in determining soil strength parameters for use in the prediction of soil failure models. Soil samples for the triaxial tests at 42% moisture content were obtained using sampling tubes. At this moisture content, the soil was not sticky and soil was easily prepared by compacting it into the soil tank by tampering lumps of soil with a metal tamper. Soil preparation for soil bin was done by mixing a given amount of water to a given weight of air dried soil in several buckets. The mixture was passed through a pugmill several times for proper mixing. Soil coming out of the chute was cut into small pieces with a cheese wire. Sampling tubes were lubricated with liquid paraffin and pushed into this prepared soil mass by hitting with a hammer and a block of wood. Test samples were later obtained by extruding the soil using a sampling auger and a split former. This procedure was not possible for soil at 56% and 70% moisture contents (dry basis) because of the sticky nature of the soil. Though soil could be packed into the split former, transferring it to the membrane stretcher would be an impossible task as the soil stuck to the wall of the split former and was difficult to extrude. Samples that were successfully prepared would get squashed once the O-ring was released. Many days were spent trying to find the best technique. Finally the chosen method was to compress the soil into a membrane stretcher with the rubber membrane fully stretched and secured with the O-rings. Once the required height was obtained in the stretcher, the O-rings were released. The enclosed sample was later transferred to the apparatus and subjected to four cell pressures up to 138 kN/m^2.

Osman (1964) used cell pressures up to 55 kN/m^2 for his clay whilst Omer (1977) used 80 kN/m^2. The confining stresses were applied using a mercury/water constant pressure system and measured using the manometer of the interconnected pore water apparatus with the triaxial apparatus. Following the technique used by Godwin (1974) as recommended by Lambe and Whitman (1969), the shear strength parameters were calculated using the equation of the Kf line from the linear regression model.

The soil-metal interface parameters were measured using a sliding resistance apparatus (Osman, 1964) since the torsional plate method was difficult to use in very wet soil due to sinking when loads were added. The sliding resistance apparatus consisted of a soil tray mounted on a trolley and driven along two rails by engaging to a hook on a driving cable. The cable in turn, was driven by an electric motor. In use, the tray was filled with soil and levelled with a spatula. The metal slider was then placed onto the soil and weights added. The slider was then connected to a spring balance by a string which passed over a small pulley. As the trolley moved relative to the slider, the steady reading of the spring balance was recorded. This reading represented the tangential force necessary to overcome the friction between the slider and the soil. The test was replicated six times and the procedure repeated for different sets of normal loads. Prior to each test, the slider was washed and wiped clean and the soil in the tray levelled with a spatula.

4.2 Clod Wetting and Clod Drying Experiments

4.2.1 Sample Preparation

Clay soil from the field was dried, broken into smaller aggregates and later passed through a grinding machine. To make up to the required moisture content, a measured amount of water was added to a given weight of soil and both were mixed in several buckets. To transform the mixture into a workable state, the clay was passed through a pugmill (Plate 4.1) at least three times for proper mixing. The soil coming out of the chute was cylindrical in shape and cheese wire was used to cut the sample into smaller pieces. A measured amount of soil was packed into a metal former of known volume with a steel rod and tamped in a systematic manner to make a specimen of known initial density. Samples were later extruded by means of a hydraulic jack and cubes representing clods of different sizes were prepared using a cheese wire (Plates 4.2 and 4.3). Block of cubes were enclosed in a plastic bag to avoid loss of moisture (Plate 4.4). Other apparatus used are as shown in Plate 4.5.

4.2.2 Clod Drying Technique

The purpose of drying was to bring the clods to different starting moisture contents without cracking. The clay clods prepared earlier were coated on all except one side with saran resin and dried slowly at 25^0C on top of an oven (Plate 4.6) to the required weights representing different initial moisture contents. An iron grill was used as a base for the prepared clods. Several drying techniques were experimented with to determine the initial moisture contents before wetting such as air and oven drying to avoid sample cracking. The use of polyethelene glycol was also proposed but it was not possible to reduce the moisture content of the clay soil to lower than 26% the reason being that the concentration of polyethelene glycol was related to the matric suction on the water retention characteristics, and the maximum suction at 15 bars gave the minimum moisture content of 26%. Further increases in suction had no effect on moisture content reduction. Drying on top of the oven at 25^{0}C was found to be the best in avoiding clod rupture and achieving consistent weight changes with time. With the air drying technique the changes were inconsistent with time due to the effect of humidity, whilst drying in the oven caused clod rupture and severe cracking apart from non-uniform moisture gradients within the clods. On top of the oven, the warm air flow was one-directional since only the lower part of the clod was not coated. The weight of clay clod was monitored every two or four hours depending upon requirements.

4.2.3 Clod Wetting Technique

The objective of wetting the clods was to study the rate of water uptake as well as to observe the moisture gradients and wetting front within a clod. Clay clods initially dried to the required initial moisture contents were placed on smooth, thin porous paper and later wetted by capillary action on a sand table (Plate 4.7). Several techniques of wetting have been described in the literature notably by Emerson and Grundy (1954), Gumbs and Warkentin (1976), Kemper and Koch (1976) and Alderfer (1950) who used capillarity, whilst Rennie (1952) wetted their soil aggregates by spraying with an atomiser. Gumbs and Warkentin

(1976) and Kemper and Koch (1966) used immersion techniques whilst Dettman (1958) wetted soil aggregates under a vacuum. In the paddy field situation, flooding or submergence is the typical method used for wetting clods. In this study, however, an earlier method of wetting clods by submergence in water proved not to be feasible since the cubes merely collapsed, presumably due to the destruction of soil structure as a result of drying. Earlier work by Tsygonov (quoted by Russell, 1938), Yoder (1936), Alderfer (1950) and Nijhawan and Olmstead (1947) indicated that soil aggregates were more stable to immersion in water at high moisture contents than when allowed to dry. Since the aim of this study was to use a non-submergence technique, a capillary method was adopted using a sand table. The samples wetted were separated from the sand by means of a porous material. According to Holmes and Marshall (1979), a suitable material with very small microaggregates that maintain a higher moisture content and hence high hydraulic conductivity over the range of matric suctions should be used. For suctions less than 30 cm, blotting paper has been recommended as it remains saturated at very low suctions. Prior to wetting, the saran resin coatings were slit open and removed with a pen knife to avoid restriction to swelling. The sand table suction was set at 10 cm since at lower suctions the clods were severely ruptured at their base. To avoid evaporation loss during wetting, the sand table was covered with a polythene sheet, secured with a rubber band. The middle part of the polythene sheet was raised to enable any water which condensed on the sheet to flow to the side rather than falling back onto the samples. This prevented large wetting errors. Each size of clod required 63 samples for three different initial moisture contents and the wetting period was limited to 7 days. Everyday three samples of each clod size were picked up for analysis by sliding a spatula underneath the clods. A total of 338 clods were required for the two confining stress conditions tested.

4.2.4 Measurement of Clod Volume and Porosity

Clod volume was determined by a water displacement method as described by Blake (1965). Clods were first stripped of the saran resin coating and weighed. Three coatings of molten wax was then applied to their surface using a soft paint brush. Wax gave a better coating than saran resin since the latter incurred moisture loss due to evaporation even after three coatings. Coated clods were first weighed in the air followed by weighing in water. The difference in weight was taken as the total volume of clod and wax. Knowing the density of wax, the volume of wax was calculated and the clod volume was later determined by deducting the volume of wax from the total volume. Porosity was calculated from the bulk density (Db) and an assumed value of 2.67 Mg/m^3 for particle density (Dp) using the equation

$$n = (Dp - Db)/Dp \quad ....(4.1)$$

4.2.5 Determination of Clod Moisture Profile

The moisture profiles of clods were determined by first slicing the clod into several pieces 5 mm thick starting from the base. Each slice was then weighed and dried in the oven at 105^0C for 48 hours. The moisture content of each layer was then calculated. For wet samples, it was convenient to use a cheese cutter. However, for dry clods, a pen knife was required to scrape the soil for every 5 mm thickness. The apparatus used are as shown in Plate 4.8.

4.2.6 Measurement of Clod Strength

Clod strength was measured by means of a drop cone penetrometer with an apex angle of 30^0 and weighing 80 grams based on the method used by Hansbo, 1957 and Towner, 1973. Depth of penetration for each wet clod was recorded prior to moisture content determination by dropping the cone onto a wet clod and the distance of the fall was measured. The centre of clod was taken as the most suitable position to drop the cone without causing any rupture to the clod. Three replicates were used for every clod size tested and data was collected everyday for the seven wetting days.

4.2.7 Measurement Of Input Parameters Into Linear Heat Flow Model

The input parameters apart from soil dimensions are soil water diffusivity and volumetric moisture content at saturation. Diffusivity is defined as the ratio of capillary conductivity to specific moisture content. The specific moisture content is in turn defined as the change in moisture content in the porous medium for a unit change in tension or suction head. Volumetric moisture content at saturation was measured by wetting several pairs duplicates of 65 mm soil cubes, for four weeks and the moisture content was determined by oven-drying at 105^0C for 48 hours. The clod porosity (n) was calculated from the dry bulk density value (Db) and an assumed value of 2.67 Mg/m^3 for particle density (Dp), using equation (4.1). The density of water was taken as 1 Mg/m^3.

Field and laboratory methods to determine diffusivity as a function of soil moisture content and soil moisture tension have been described by Klute (1972). The field methods are in general laborious and demand a high degree of instrumentation whereas many laboratory methods are time consuming, require special equipment and often do not represent the hydraulic properties of field soils. Bruce and Klute (1956) earlier developed a laboratory method of measuring diffusivity in horizontal columns of soil for the infiltration process. Their analysis required that water content be a function of a variable dependent on distance and the square root of drying time. For the same conditions, Gardner (1959) developed a slightly different analysis and applied it to the process of evaporation. In both studies, comparatively long columns of remoulded soil were used. Recently Arya et al. (1975) proposed a new laboratory method for obtaining diffusivity by modifying Gardner's technique using short natural soil cores. The method is rapid and requires no special and complicated instrumentation. Arya et al. (1975) used the diffusivity equation of Bruce and Klute (1956) with the following initial and final boundary conditions;

$\theta = \theta_i \quad x > 0,\ t = 0$ .....(4.2)

$\theta = \theta_{sat} \quad x = 0,\ t > 0$ .....(4.3)

where θ_i = the initial volumetric moisture content

θ_{sat} = volumetric moisture content at saturation

x = length of soil core

t = time

Diffusivity values could then be calculated from moisture-distance functions by the following equation;

$$D(\theta_x) = 1/2t\ (dx/d\theta)_{\theta x} \int_{\theta_i}^{\theta_x} x d\theta \quad ....(4.4)$$

where $D(\theta_x)$ is the soil water diffusivity as a function of moisture content. To transform to an ordinary differential equation, the Boltzmann variable, $\lambda = xt^{-1/2}$ is normally used. Integration using the given boundary conditions yields the following equation

$$D(\theta') = -1/2\ (d\lambda\ /d\theta)_{\theta'} \int_{\theta_i}^{\theta'} \lambda(\theta) d\theta \quad ....(4.5)$$

where D and $d\lambda\ /d\theta$ are both evaluated at moisture content θ'. The moisture content versus position at a series of fixed times or the moisture content versus time at a series of fixed positions can be used to construct a plot of λ versus θ. If the flow is described by the non-linear diffusion equation and the boundary and initial moisture contents are constant, the transformed moisture content-distance-time data should give a unique $\lambda(\theta)$ function. The derivative and integral of equation (4.5) can then be evaluated from this plot either graphically, numerically or by analytical means if an equation for the fitted curve is available.

Since the Arya et al. (1975) technique is simple, low cost, quick and less laborious, this technique was adopted to measure the soil water diffusivity value. Air dry aggregates were ground and passed through a 2 mm sieve, packed into columns 10 cm long tube having a 3.25 cm diameter. To arrive at the required moisture content before packing, a measured amount of water was sprayed onto a given weight of soil. Soil cores were later extruded and transferred to another split tube. The tubes were covered with tapes and secured with rubber bands. Three replicates of soil cores at two different moisture contents were placed in a beaker filled with water and wetted for four weeks. Saturated samples were then sealed at both ends and allowed to equilibrate for four weeks after which one end of the core was opened and hot air was blown over the wet surface with a commercial paint stripper from a height of 5 cm. Evaporation was determined by periodic weighing of the soil core. The accuracy of this technique depends on the following conditions being satisfied:

a) That cumulative evaporation be proportional to the square root of drying time.

b) That evaporation be continued as long as the bottom of the core remained unchanged.

Both conditions were established by a number of preliminary tests. The time during which evaporation was proportional to the square root of drying time was strongly influenced by the initial wetness of the sample and the potential evaporation rate. At the conclusion of each test, the bottom seal of the core was peeled off and the soil was sliced in 10 mm lengths. Their gravimetric moisture contents were later determined by oven-drying at 105^{0}C for 48 hours. Initial moisture content of the core was determined from the cumulative water lost from all samples upon oven-drying plus that lost in evaporation before slicing.

4.2.8 Measurement Of Input Parameters For Jarvis and Leeds-Harrison's Lateral Sorption Model

The unknown input parameters in the lateral sorption model are the fractional wetted depth, f, and the sorptivity term assuming the fractional wetted ped surface area, a, as 1/6 since it is fully saturated. If the height of the soil cube is considered to be one layer, the value of k will be unity and the layer thickness, Δz, is equivalent to the height of soil cube. In the above model, the total ped surface area per unit volume of soil, A_v, was taken as 6/d where d is the ped width (Jarvis and Leeds-Harrison, 1987). The fractional wetted depth was assumed to be unity since the model was based on the equation of infiltration as proposed by Philips (1957a). Having substituted all the above parameters into the above model, the predicted values were compared with the experimental data.

The other parameter required in the above model is the sorptivity term. This term was introduced by Philip (1957a) in his well known two term infiltration equation. As described by Philip, sorptivity is a measure of water uptake by soil without gravitational effects. Several methods for obtaining the sorptivity value have been well described by Chong and Green (1983). These methods, however, were all based on field measurements. Some involve rather complicated mathematical calculations or require measurements of certain parameters that are both tedious and time consuming. Young (1981) on the other hand, developed a simple relationship given as

$$S(\theta) = 6.3(\theta_{sat} - \theta_i)^{0.5}\ Ksat^{0.25} \qquad ....(4.6)$$

where θ_{sat} = volumetric moisture content at saturation

θ_i = initial volumetric moisture content

Ksat = saturated hydraulic conductivity

For this study the above equation was used to calculate the sorptivity value. The saturated hydraulic conductivity value was determined using a falling head permeameter. Volumetric moisture content at saturation was determined by wetting soil clods for four weeks before being oven-dried at 105^0C for 48 hours. The clod porosity was calculated using equation (4.1) as described earlier. These measured values were substituted into equation (4.6) to calculate the sorptivity term. The known sorptivity term was later substituted into the lateral sorption equation to calculate the height of water infiltration.

4.3 Soil Tine Interaction Studies

4.3.1 Description of Soil Tank

Tests were conducted in a soil tank 1.5 m long, 0.5 m wide and 0.3 m deep containing an electrically driven carriage which ran on rails above the soil tank (Lawrance, 1978). The tool holder frame was designed and fabricated (Plate 4.9.) and the tank could be pulled out towards the operator for soil packing. A plastic sheet was used in the base for easy mixing and remoulding of soil without the soil sticking to the tank.

4.3.2 Instrumentation

4.3.2.1 Force Measuring Dynamometer

The forces acting on the tines were measured by means of an extended octagonal ring dynamometer designed by Godwin (1974). This dynamometer was fabricated from EN 24 steel heat treated to an ultimate tensile strength of 1540 N/m^2 and had an elastic modulus of 207 GN/m^2. The dynamometer consisted of 12 strain gauges grouped into three bridge circuits. Four strain gauges were interconnected to form a single bridge circuit. The three bridge circuits were then connected to a single conveying cable.

4.3.2.2 Signal Conditioning and Recording Equipment

The output from each strain gauge bridge circuit was amplified using a dc differential amplifier which also supplied the working potential for the bridge circuits. Output signals from these circuits were fed directly into a multichannel ultraviolet oscillograph. The traces obtained from the ultraviolet oscillograph were continuous recordings of the horizontal and vertical forces over the entire distance through which the tines were winched. Mean area enclosed between the traces was found by direct planimetering. Planimeter measurements were taken over the most uniform 100 mm interval of the force traces. The mean heights of traces with respect to the zero settings were determined and multiplied by their respective calibration constants to obtain the corresponding forces.

4.3.2.3 Calibration of Dynamometer

The dynamometer was loaded horizontally and vertically at different distances from its centroid. Signals from the Fx and Fz bridges were recorded for both loading and unloading conditions. To measure the interaction of a vertical force on the horizontal force bridge, (Fx), the procedure was repeated with the horizontal strain gauge bridge output voltage measured. Likewise, the output voltage of the vertical strain gauge bridge, (Fz), was measured to find the interaction of a horizontal force on the vertical force bridge. Throughout the experiments, the gain settings were such that a displacement of the signal spot of one cm from the reference zero, represented a force of 327 N for Fx and 226 N for Fz bridge circuits respectively. The calibration data are shown in Tables A5.35 and A5.36 in the Appendix. A diagram showing typical forces acting on the dynamometer as well as strain gauge bridge circuits is shown in Figure 4.1.

4.3.4 Soil Preparation

The experimental soil was excavated from a cultivated field by digging two trenches to a depth of one meter. Wet clay soil from the field was dried, broken into smaller aggregates and later passed through a grinding machine. To prepare the soil to the required moisture content, a measured amount of water was added to a given weight of soil and both were mixed thoroughly in several buckets. To transform the soil into a workable state, the clay soil was passed through a pugmill three times. Further mixing and remoulding was carried in an auxiliary soil tank. To obtain equilibrium, the soil was left for as long as one week before it was transferred to the main tank.

In the main tank, soil preparation was done by pummelling and pressing each lump of wet soil using both hands and barefeet. To achieve the required depth, the prepared soil was levelled using a specially fabricated blade (Plate 4.10) which was fixed to the carriage and could be moved along the tank over several steps. Each cut of clay was about 150 mm long and when complete, the surcharge was removed from the soil surface. The surcharge was later lumped to one side and the next incremental run was made. This was repeated several times until the required level was achieved. Rubber gloves were worn to avoid soil sticking to the hands. The tool holder for single and multiple tine experiments is shown earlier in Plate 4.9.

The moisture content of the soil in the tank was monitored daily and when necessary water was added to maintain the moisture content to within one percent. Water was supplied through a pressurised container and sprinkled via a fine nozzle. The wet soil was then mixed by smearing and rubbing by hand and left for about one week under a plastic cover to allow equilibrium to be established and to avoid evaporation loss.

4.3.5 Tine Experiments

After the soil was prepared, plate sinkage tests were carried out to determine the uniformity of soil preparation. A tine was then fixed to the tool holder and after switching on the signal amplifying and recording equipment and allowing an adequate interval for the ultraviolet oscillograph to reach stability, the reference zero, gain and attenuator settings were checked for the two channels in use. This was achieved using electrical calibration shunt resistance circuits to obtain the approximate signal levels. The dynamometer was then balanced under the zero load condition and the tine was then pulled through the soil. Horizontal and vertical forces were amplified using a strain stall amplifier and recorded on the ultraviolet oscillograph paper. The motion of the tine through the soil was also recorded on a video film.

After each run, the tine was dismantled and the tank pulled out. The height and extent of soil heave were measured using a profile meter with rods spaced 10 mm apart. Each rod was fitted with a plastic plug to avoid the rod from penetrating the soft and wet soil. Each profile measured was later transferred onto a transparent paper. Photographs of selected tine performance were also taken for comparison purposes. Prior to every run, each tine was washed and wiped clean with a piece of cloth. Three soil samples were collected for bulk density and moisture content determination using standard bulk density rings of known volume. Each ring was pressed into the soil and later dug out with a spatula. Additional soil sticking to the ring was wiped clean with a piece of cloth. After weighing, the soil samples were oven dried at 105^0C for 48 hours. Dry bulk density and moisture contents were later computed.

4.3.6 Device For Measuring The Soil Profile

The profile of the cross section of the disturbed area was measured using a profile meter. This instrument was a simple rectangular aluminium box consisting of a number of laterally spaced vertical rods or legs, capable of sliding upwards or downwards. When the meter was superimposed across a section of the disturbed zone, the legs were adjusted so that their bottom edges formed points on the outline or profile of the contour of the disturbed cross section. The legs were then locked in position by means of a clamping screw so that the meter could be removed. The meter was then positioned on a sheet of paper and an outline of the cross sectional profile was obtained by drawing a line connecting up the bottom edges of the legs.

4.3.7 Soil Disturbance Pattern

In tine interaction studies, the observation of soils under conditions of failure often provides the basis for the development of important theories leading to solutions of the forces and deformations at failure. Several techniques were used in the past but the most successfully employed method has been the glass sided tank to study deformation patterns and failure boundaries. In 1948, Peynircioglu presented an impressive photographic study of failure boundaries in support of his work on shallow foundations. In the same year, Bekker (1948) photographed the wedge formation beneath a strip footing to illustrate the correct angle at which the slip planes form. In more recent years, some of the noteworthy efforts in use of this technique include the photographing of soil deformation and particle displacement beneath a rigid wheel by Wong (1966) and the work of Hettiaratchi (1967) in his treatise on passive earth pressure. A notable contribution in recent years has been the work of Witney (1968 and 1969) in that a considerable effort was expended in determining the effect of side wall friction on failure patterns and the use of various lubricants between glass and soil. Others include Harrison (1973), Godwin and Spoor (1977, Zhang and Shao (1984) and Salokhe and Gee Clough (1988).

Another technique worthy of mention is the use of X-ray equipment to obtain photographs of soil during deformation. This technique has been developed at Cambridge to quite an advanced stage (Roscoe, 1963). The X-ray test apparatus was used by May (1968) in an impressive study of dilatation along failure boundaries. The radiograph technique has also been used by Booyd and Windisch (1966) to record soil movements beneath a rigid wheel and tine studies by Ichiba et al. (1987).

Recently a bead tracer technique has been used in determining soil deformation (Spoor and Fry, 1983) and soil compaction (Seig, 1986). Coloured beads were accurately positioned in rows at various depths. Bead positions before and after each test were recorded in the X, Y and Z planes using a vernier X, Y, Z plotter. The method used to estimate relative net compaction or loosening effects was based on the assumption that any beads located initially at the same depth (Z) and lateral distance (Y) from the tine in the direction of tine travel (X) will behave in a similar manner to the soil particle movement. This assumption was considered valid for homogeneous soils. The technique gives the three dimensional nature of soil disturbance generated by any simple tines or tyres.

In this study, two different methods described above were employed namely a bead tracer technique and a talcum slurry technique used in conjunction with a glass sided tank. The purpose of the tests in the glass sided tank was to give evidence in support of the description of the deformation pattern obtained by the use of the bead tracer technique.

4.3.7.1 Bead Tracer Technique

Assessments of soil disturbance were made using two independent approaches, the location of the shape and extent of soil heave and a determination of the trajectory and movement of soil particles within the entire disturbance area after the passage of tine. The zone of detailed study was 101.6 mm above the working depth fixed at 152.4 mm. Immediately following the passage of an experimental tine, the shape and extent of heave were measured using a profile meter and a surveying ruler. The trajectory and relative movements of soil particles during disturbance was measured by means of the bead tracer technique. The extent of surface heave was determined for all tine widths at three depths while the bead tracer technique was only used for the 50.8 mm tine operating at 152.4 mm depth. Soil trajectory studies were conducted at 70% moisture content (dry basis) using plastic beads, each about 5 mm in diameter and tied with a flexible string for easy location (Plate 4.11). These beads were large enough to be easily detectable yet not so large as to cause a change in the soil failure pattern.

The beads were positioned as follows. After the soil had been prepared and levelled, two parallel lines 150 mm apart and perpendicular to the direction of tine travel were drawn on the soil surface. Three positions, 30 mm apart from the tine center line were marked. For each position marked on the surface, one plastic bead with a flexible string was implanted into the soil to the required depth using an aluminium rod through a guiding frame. Each position on the surface had three beads positioned laterally and vertically forming three layers from the surface. Beads positioned in the third layer were implanted first followed by those positioned in the second and first layers respectively. Prior to each penetration, the aluminium rod was wiped clean and oiled with liquid paraffin to avoid soil sticking to the rod and causing unnecessary movement in the soil.

When all the plastic beads were positioned with the strings protruding from the top, the 50.8 mm tine was pulled through the soil at a travelling speed of 0.1 m/s. This tine was selected because it caused the greatest disturbance. Immediately after the run, the tine was dismantled and the tank pulled out. Each bead was then located by slicing the soil with a spatula initially wiped with a wet cloth. The process was very time consuming. Once located, the position of each bead was measured in three directions from the tine centre line using a ruler. A similar procedure was repeated for different rake angles. After the experiments, three samples were collected for moisture content and bulk density determinations. To estimate the relative net compression or dilation effects, the technique reported by Spoor and Fry (1984) was adopted.

4.3.7.2 Talcum Slurry Technique

To observe the failure pattern in the vertical plane containing the centre line of the tine, a glass sided tank was used. Plane simple tines 12.5 mm wide at three rake angles and operating at 101.6 mm depth, whilst firmly held against the sheet of glass were pulled through a mass of cohesive soil made up of Kaolin clay and a mineral base oil. Shell Carnea 21 was used since it has less additives than other oils and hence a lower health risk than other oils of similar viscosity (Omer, 1977). The glass was assumed to be the axis of symmetry of the tine in the direction of travel (Godwin, 1974). The effective tine width was therefore twice the actual tine width. The use of an artificial soil in the study was due to the difficulties in maintaining relatively constant strength properties with the natural soil apart from avoiding the problem of stickiness to the glass. Hanomoto (1957) has listed several beneficial properties of an artificial soil namely:

a) The strength properties of the soil should not change with time, temperature or humidity.

b) The soil mix should be capable of representing a wide range of soil types and soil conditions.

c) The soil should have strength properties such that when disturbed it can return quickly to its natural state repeatedly without changing its strength properties.

d) The artificial soil should behave reasonably like a natural soil.

According to Korayem (1966), the strength properties of artificial mixtures were found to compare well with values obtained from many natural soils. However, using artificial soil mixtures of clay-sand-oil/ethylene glycol, Reeves (1966) found that both mixtures have drawbacks when the ideal characteristics of Hanomoto (1957) were considered, especially when the moistening agent concentration was varied. This means considerable work is required to check the strength properties of the artificial soil.

In this study, a mixture of 550 ml/kg of soil was used since it gave the equivalent strength of clay at 56% moisture content. Greater quantities of oil, about 628 ml/kg, gave the equivalent strength of clay at 70% moisture content but unfortunately, the resulting mixture was too soft to handle. A lower concentration for an equivalent strength of clay at 42% mixture content was too stiff to compact in the soil tank. The shear strength of the artificial soil was determined using the triaxial apparatus. Despite the same strength, the soil lacked the smooth feeling and the viscosity of a real wet clay soil. The artificial soil was somewhat spongy and would not remain homogeneous when mixed. Boundaries between layers would still be visible when two lumps of soil were pressed into each other.

Once the artificial soil was prepared, the soil tank was laid on its back, the glass front removed and soil packed into the tank. The necessary amount of excess soil was removed in thin layers to provide the desired depth for soil cutting. A 100 mm grid of talcum slurry was prepared and grids were marked horizontally and vertically on the soil surface by means of a plastic syringe (Plate 4.12). After the talcum slurry had dried for about 15 minutes, the front part of the tank was put back and the plate glass, initially wiped with liquid paraffin, fixed. The soil tank was then placed in its upright position and lifted onto the rails by means of a hydraulic crane. The tine was bolted into its initial position, the rails and tine carriage being assembled last. Once ready, the tine was slowly moved and after a short distance, the tine carriage was stopped.

The deformed grid of talcum slurry was then traced onto a transparent paper.

4.4 Soil Puddling Experiments

4.4.1 Design of a Laboratory Puddler

The laboratory puddler consisted of a mechanical stirrer in the form of a kitchen mixer to simulate the rotary cultivator currently popular in rice field preparation. Blades 2 mm thick were welded to a central rod 6 mm in diameter and made from mild steel. The length of the puddler was 80 mm and the effective diameter was 50 mm. The shape of the puddler is shown in Plate 4.13.

4.4.2 Instrumentation

The instrumentation required consisted of a 50 Watt electrical motor, a speed controller, a voltage regulator and a watt-meter. The motor was used to drive the stirrer while the speed controller and voltage regulator were used for controlling the motor speed. The watt-meter measured the power input.

4.4.3 Soil Preparation

A clay soil from the field was air dried, broken into smaller aggregates and sieved, aggregates in the size range 10 to 12 mm diameter being collected. Each 400 gram weight was kept in a plastic bag to conserve the moisture content prior to testing.

4.4.4 Calibration of Watt-meter

The energy output for each motor speed was calibrated with the help of a tachometer.

4.4.5 Aggregate Size Distribution Analysis

Aggregate size distribution of the puddle soil was determined by wet sieving using the apparatus (Plate 4.14) for water stable aggregates analysis (van Bavel, 1952). After each puddling experiment, the total content of each beaker was poured into a nest of sieves (Plate 4.15), immersed in a tub of water and agitated vertically at a rate of 30 strokes a minute. The agitation was carried out for 500 strokes to separate the fines from the coarser aggregates. This method was adopted since the particles would stick together if dried and render it difficult to sieve the whole mass by dry sieving. Material retained on each sieve was washed into a drying tin and dried in the oven at $105^{0}C$ for 48 hours and the percentage of aggregate retained calculated. Percentage distribution of aggregates below 0.5 mm diameter (mean-weight diameter) for different water soil ratios and stirring times were analysed statistically at 95% confidence level using the ANOVA package. The mean weight diameter is the single value of the degree of aggregation. This was calculated according to the method of Youker and Mc Guinness (1957) which states that

$$Y = 0.876\ X - 0.079 \qquad \text{........(4.7)}$$

where X is the sum of the products of aggregate size times weight of aggregates within that size and Y is the mean weight diameter.

4.4.6 Measurement of Soil Bulk Density

Wet bulk density values of the resultant puddle were measured using a litre beaker of a known base area (Plate 4.16).

The oven dried weight of aggregates was earlier determined by drying a representative sample of the air dry aggregates in the oven at 105^{0}C for 48 hours. Volume of puddled soil was determined by multiplying the height of puddled soil (without free water) after 2 hours of settlement with the base area of the beaker.

CHAPTER 5.0 RESULTS AND DISCUSSION

5.1 Soil Physical and Mechanical Properties

Figures 5.1 and 5.2 show the physical and mechanical properties of the Wicken series clay soil which has a lower plastic limit of 24% and an upper plastic limit of 90%. The water retention characteristic with a field capacity of 41.5% and a permanent wilting point of 29.4% is shown in Figure 5.3. The soil shear strength values were 29 kN/m^2, 16 kN/m^2 and 6 kN/m^2 at 42%, 56% and 70% moisture contents respectively. The soil was frictionless but had an angle of soil-metal shearing resistance of approximately 20^0 at all moisture contents. The soil-metal shearing resistance values were 1.14 kN/m^2, 0.9 kN/m^2 and 0.25 kN/m^2 at 70%, 56% and 42% moisture contents respectively. The relationships between soil shear strength and soil-metal shearing resistance values with moisture content are presented in Figure 5.4. A summary of soil properties is given in Table 5.1. Detailed test results are presented in Tables A5.1 to A5.7 in the Appendix.

5.2 Clod Wetting and Drying Studies

5.2.1 Effect of Wetting On Clod volume, Dry Bulk Density and Moisture Content Profile Under Two Stress Conditions.

Results of volume, dry bulk density and moisture content changes for three soil clods over a wetting period of 7 days under two stress conditions are presented in Tables A5.8 to A5.19 in the Appendix. The initial volume, dry bulk density and moisture content values are also given for comparison. At average initial moisture contents of 12% and 22% (dry basis), all clods experienced volume change when wetted under suction as shown in Figures 5.5 and 5.6. The driest clods changed most, with little volume change when clods were initially very wet at about 38% moisture content (Figure 5.7). The volume of the driest clod increased rapidly initially, but the rate of increase decreased with wetting time, giving a parabolic relationship. For the confined wetting case, the percentage change in volume was greatest with the smallest clod followed by the medium clod. The unconfined clods (small and medium size) were initially larger during preparation which had the effect of increasing their initial volume prior to wetting. Nevertheless, the relationship with wetting period shows a similar trend to that of the confined clods. It would be expected that the clod volume should increase with wetting time. However, this process was impeded in the unconfined clods by the formation of horizontal cracks separating the swelling and non-swelling parts. These cracks tended to restrict upwards water movement thereby reducing the swelling potential of the upper soil layer. The increase in volume was therefore always greatest with the confined clods. At 38% moisture content, the change in clod volume was very small regardless of the confining conditions. The effect of stress condition, clod size and wetting period on clod volume was statistically significant at 95% confidence level at all moisture contents. The results are summarised in Table 5.2.

The change in dry bulk density for the three different initial moisture contents (Figure 5.8) was greatest with the smallest clod when under confined conditions and this corresponded with the largest increase in clod volume. This might be explained by the delayed swelling effect experienced by the smaller unconfined clod whereby the flow of water was restricted by the existence of horizontal cracks near its base in the unconfined situation. By contrast, the largest clod experienced greater reductions in dry bulk density when stress was not applied (unconfined condition). At 22% moisture content, under confined conditions, the smaller clods experienced the largest reduction in dry bulk density followed by the medium and large clods. Under unconfined conditions, the pattern was irregular. Statistically, the effect of stress condition, clod size and wetting period on dry bulk density was significant at 95% confidence level. A summary of the results is presented in Table 5.3.

Results on the rate of water uptake within the first 10 mm layer of each clod (Tables A5.20 to A5.23 in the Appendix) under both confined and unconfined conditions presented in Figure 5.9 show that the smallest clod had the highest percentage moisture content (weight basis) compared to medium and large clods. The relationship of percentage moisture content with time was parabolic for both confined and unconfined conditions. At 12% initial moisture content, a slight deviation was observed after 1 day wetting period whereby the increase in water uptake by the largest clod was greatest compared to medium and smaller clods when they were unconfined. This was in contrast to the results obtained when the clods were confined where the smallest clod had the highest water uptake over the entire wetting range. This discrepancy could be due to the presence of cracks formed across the smaller clods which restricted the easy passage of water flow upwards. Further movement would only be possible after the cracks had been filled completely with water. These cracks were not noticeably present in the large clods. Both small and medium clods showed a similar pattern at 22% moisture content. At 38% initial moisture content, the water uptake was very small regardless of stress conditions. The effect of stress condition, clod size and wetting period on soil water uptake was statistically significant at 95% confidence level. A summary of the result is presented in Table 5.4.

Detailed measurements of the moisture profiles within clods are given in the Appendix (Tables A5.24 to A5.29) for both unconfined and confined conditions. The moisture profiles within a medium clod wetted under confined and unconfined conditions are shown in Figure 5.10 for very dry and dry initial states. The rate of increase in water uptake was greatest within the first wetting day for the first 10 mm layer for both confined and unconfined conditions with the unconfined condition giving the lower value. The slope of the moisture content-wetting time curve for the confined case was lower compared to the slope of the moisture content-wetting time curve for the unconfined case which shows a hyperbolic relationship. For wetting times greater than one day, the rate of decrease in slope for the unconfined case was lower and the profile was more uniform after 5 days than in the confined case. Obviously water began to flow upwards after the cracks were filled with water. The transition point at the 10-20 mm boundary indicates the formation of cracks which impeded water movement.(See Figure 5.10i).

The above results also show that the rate of water uptake was greatest when the soil was initially very dry but the maximum moisture content reached was somewhat less than full saturation since greater resistance was met due to reduced air filled porosity as a result of shrinkage during drying. The greater rate of increase initially might be explained by the formation of vertical cracks during drying which tended to reduce surface contact area with the wet sand incurring a bigger rise in water column for a given water quantity at a given suction. At a slightly higher moisture content, the rate of water uptake was much lower but nevertheless, showed the same trend as above where the maximum moisture content achieved was less than the saturation limit due to the presence of air in clod microspaces. When the clods were initially very wet, very little water was transported upwards due to very small or almost zero air filled porosity.

During wetting, the lower part of each clod tended to swell horizontally and in the process some soil slaked. Cracks were much more extensive in the case of unconfined clods. This phenomenon has been described by Russell (1971) whereby dry clods which swell on wetting tend to produce more cracks then initially wet clods. This is due partly to uneven swelling of different parts of the clod and partly due to the disruptive effect of the adsorbed air which is displaced on wetting but is entrapped by water films. Soil slaking resulting from the sudden wetting could be due to the inability of the cohesive bonds within the clod to withstand the swelling pressures. Dettmann (1958), on the other hand, stated that slaking is always associated with rapid intercrystalline swelling of the clay. The readjustment of the internal geometry of the clay is reported to produce some dislocation but no disruption. This structural distortion as a result of uneven strains within an aggregate caused by swelling reduces its stability (Panabokke and Quirk, 1956; and Marshall and Holmes, 1979).

The results on water uptake for the unconfined case differed from the findings of Emerson (1955) who noted a slower water uptake with time for the subsoil core than for the surface crumb. He attributed this as due to the absence of cavities into which the clay crystals could expand. This difference could be due to the different technique used by Emerson who wetted his field clods by dripping water vertically onto a clod via a syphon. Information on crack formation as well as the initial moisture content of samples was not available. It is expected that soil clod wetted by dripping would become saturated faster since downward flow of water is further aided by the force of gravity and hence increase the chance of swelling uniformly. Emerson used field samples where the internal cohesive bonds were still stronger whereas the samples used for this experiment were remoulded clay which cracked when wetted under unconfined condition as a result of greater swelling. Yong and Warkentin (1975) reported that unconfined swelling was greatest when the soil has been reworked and orientated. This phenomenen was later confirmed by Spoor et al. (1985b). Remoulded soil is frequently more susceptible to unconfined swelling than undisturbed soil since remoulding causes the breakdown of many of the cohesive bonds responsible for soil aggregate stability. These bonds do not reform immediately and may, depending on the degree of orientation, be of different magnitude when reformed. The magnitude of the strength components depends on packing method, moisture states, swelling behaviour, clay content and clay mineralogy (Spoor et al., 1982). Crack development due to swelling was also observed during irrigation of initially dry soil by Stengel (1988). The influence of cracking on water movement was also discussed. Cracks which appeared in front of the wet zone of the samples acted as preferential pathways due to water capillary rise inside them. This phenomenon strongly influenced water uptake kinetics and contributed to progressive cracking of the whole sample volume.

From the above studies, the rate of water uptake was found to be greatest when clods were initially very dry. Continuity of flow was better when the remoulded clods were confined. Imposing loads helped reduced swelling and hence reduced crack formation. The rate of infiltration into the clod decreased with increasing initial moisture content confirming earlier observation by Philip (1957b). At low moisture contents, the soil water within the clods would be under tension. On wetting water would move into the clods under the action of the potential gradient, the moisture tension in the clods would decrease and the clods would swell. This swelling process would continue until the potential gradient was reduced. Under confined conditions, further swelling would be restricted resulting in the building up of swelling pressures within the clod. This would reduce the moisture tension and the potential gradient. Equilibrium would be established when the potential gradient becomes zero. Smaller clods tend to absorb water faster than larger clods for a given initial moisture content under confined states. When clods were unconfined, the rate of water uptake tended to be greater with larger clods compared to the smaller ones as time progressed due to the formation of horizontal cracks in the smaller clods. These cracks were absent in the large clods. Hence the effect of confining was to improve water infiltration when the initial conditions of clods were very dry. Confining had no effect on water infiltration when the initial conditions of clods were very wet.

5.2.2 Effect of Wetting On Cone Depth

Results on cone penetration depth for confined clods at 22% and 38% moisture contents are shown in Figure 5.11 and presented in Table A5.30 (in the Appendix). As wetting time increased, the depth of cone penetration increased up to a point limited by the shape of the cone. The relationship was parabolic at 22% moisture content confirming that soil becomes softer and weaker as moisture content increases thereby increasing the depth of penetration. The smallest clod had the highest value since the wetted depth was greater. At 38% moisture content, the relationship was nearly linear horizontally. The smallest clod showed a similar trend in having the highest penetration depth. The effect of clod size and wetting period on cone penetration depth was statistically significant at 95% confidence level. Theoretically for the same moisture content, the depth penetrated should be the same, however, the largest clod had the lowest depth. This could be due to the presence of greater mass of soil surrounding the cone tip and restricted the sideway soil movement as the cone dropped into the wetted soil layer. The smaller clod had less confining stress and hence tended to move sideways much more easily incurring a greater drop in penetration depth. Table

5.5 summarises the results on the effect of clod size and wetting period on depth of cone penetration for two initial moisture contents.

The above results show that depth of cone penetration was greatest in the smallest clod and corresponded with the parabolic relationship between water uptake and wetting time when the initial condition was dry. The effect of increasing water uptake weakened the wetted layer and became soft, thus, enabling the cone to drop further. At higher initial moisture content, the depth of cone for different wetting period was almost the same as the initial depth before wetting, giving rise to almost a linear relationship. The smallest clod experienced the greatest penetration depth compared to the largest clod. This difference was due to the presence of greater mass of soil surrounding the tip of cone which restricted the sideway soil movement as cone moved into the soil.

5.2.3 Effect of Drying On Clod Volume, Dry Bulk Density and Moisture Content Profile.

Results of volume, dry bulk density and moisture content changes for three soil clods over a period of 120 drying hours are presented in Tables A5.31 to A5.33 in the Appendix. The initial volume, dry bulk density and moisture content values are also given. Volume change occurred on all clods on drying and corresponded with an increase in dry bulk density values as shown in Figure 5.12. The rate of change in dry bulk density was greatest with the smallest clod followed by the medium and large clods confirming earlier findings by Gumbs and Warkentin (1976). The maximum dry bulk density of the smallest clod was reached within about 24 hours after which there was very little change as drying time progressed. The medium clod took about 48 hours to approach its peak whilst the largest clod took almost 96 hours beyond which further increases were small. The rate of reduction in volume followed a similar trend. The greater rate of reduction in volume in the initial stage suggests that the clods were undergoing a normal shrinkage process (Keen, 1931) followed by residual shrinkage (Haines, 1923) when the volume decreased less rapidly than the water content as air entered the soil. The time taken by the clods to reach their stabilizing state could be considered as the transition point between normal and residual shrinkage. Results from the shrinkage curve as shown in Figure 5.13 indicate that the transition from normal to residual shrinkage occurred at about 16% moisture content (dry basis) for the smallest clod. This corresponded to about 96 hours of drying at 25^{0}C. The transition points for the large and medium clods were not so distinct, presumably still undergoing normal shrinkage over the range of drying period tested. Holmes (1955) found that the matric potential at which the transition from normal to residual shrinkage occurred in his remoulded clay soils was of the order of -10^4J/kg (-100 bar).

The experimental results given in Figure 5.14 show that the smallest clod dried the fastest followed by the medium and the largest clods. This trend towards a greater volume reduction as well as the largest dry bulk density change in the smallest clod might be explained by the large surface area/volume ratio compared to a bigger clod which has a small surface area/volume ratio. Hence, for a constant heat intensity, rate of water removal would be rapid in a smaller clod. Further measurement within the first 10 mm layer of each clod (Table A5.34, in the Appendix) showed that the rate of water loss within the smallest clod was the greatest within 24 hours of drying and had the lowest moisture content over the entire period. The moisture gradients within each clod initially dried at both ends are shown in Figure 5.15. Each value is a mean of three replicates. Larger clods required longer drying period to arrive at a uniform moisture profile within as compared to smaller clods. Analysis of variance at 95% confidence level showed that clod size and drying time had significant effects both independently and in interaction with each other on clod volume, dry bulk density and moisture content.

5.2.4 Input Parameters Into Soil Infiltration Models.

5.2.4.1 Linear Heat Flow Model.

The infiltration model was based on the linear flow of heat into a solid (Carslaw and Jaeger, 1959). Since the dimensions of the clod are known, the only parameters requiring measurement would be volumetric moisture content at saturation and the water diffusivity value. The volumetric moisture content at saturation was 0.523 cm^3/cm^3 whilst the initial volumetric moisture content was 0.35 cm^3/cm^3. The diffusivity coefficient at an initial volumetric moisture content of 0.35 cm^3/cm^3 obtained by graphical method was 4.36 mm^2/day. A typical example of the relationship between evaporation and the square root of drying time is shown in Figure 5.16. The required linearity between cumulative evaporation and the square root of drying time was achieved after 3 minutes for the higher bulk density core whilst the lower dry bulk density sample achieved linearity after 2 minutes. The length of time before linearity was reached might be influenced by the hydraulic properties of the soil whereby soil packed at a higher dry bulk density tended to exert greater resistance to flow. For a majority of soil cores, evaporation could be safely continued for a period of 64 minutes before the moisture content at the sealed end dropped significantly below its initial value. A typical example of moisture content distribution through a sample is shown in Figure 5.17 whilst Figure 5.18 shows the relationship of volumetric moisture content against λ.. Other parameters required were as follow:

a) Thickness of clod, a = 60 mm

b) Thickness of each soil layer, r = 10 mm

c) Duration of wetting, t = 7 days

d) Summation limit, N = 100

These values plus the diffusivity term were substituted into equation (2.4) to determine the final saturation level of each 10 mm layer from the wetted surface for a period of 7 days. The calculation was done on a Vax computer. The calculated and the experimental percentage saturation levels of each soil layer following a 7 day wetting period for a 60 mm soil cube are presented in Table 5.6. Values at and above 100% are considered fully saturated. Deviation from experimental results could be due to the exclusion of the swelling effect and error in measurement. The error in moisture content determination might have arisen due to the presence of wax which was difficult to separate from the soil clod. The upper layers tended to lose water by evaporation probably due to the change in humidity in the room. Results for 1 and 7 day wetting periods shown in Figure 5.19 show close agreement between the experimental and the predicted percentage saturation levels. A computer programme to calculate the percentage saturation level within a clod is given in Appendix B.

5.2.4.2 Lateral Sorption Model

The saturated hydraulic conductivity measured was 0.233 mm/day. The volumetric moisture content at saturation was 0.523 cm^3/cm^3 whilst the initial volumetric moisture content was 0.35 cm^3/cm^3. These values were substituted into equation (4.6) to calculate the sorptivity term which gave a value of 1.80 $mm/day^{0.5}$. Data presented in Table 5.7 and in Figure 5.20 show that the model underpredicts the experimental results by about 50% on the small clod while the difference in value for the large clod is only about 8%. The results also show that the smallest clod required the shortest time to achieve complete saturation compared with medium and large clods because of greater water uptake. The increase in height of infiltration for the smallest clod was more rapid for wetting periods less than 5 days but tended to slow down thereafter. The difference in height of infiltration between clods could be explained by the fact that smaller clods have smaller base area and hence for a given water uptake, the height of infiltration would be higher compared to a bigger base area. Besides, the slow swelling process experienced by the largest clod would tend to restrict upward soil water movement, the water tending to move horizontally instead, resulting in a lower height of infiltration. The sorption model clearly shows that the measured value of infiltration using the numerical equation proposed by Young (1981) was appropriate only for a larger clod as compared to the smaller clod. The under prediction of results for the smaller clods might be explained by the smaller sorptivity value. This could be due to the lower saturated hydraulic conductivity value obtained since the soil was structureless and compacted. The limitation of the numerical equation is that it disregards the effect of clod size. The actual values obtained by regressing the experimental data show that the smallest clod had a value of 5.96mm/day$^{0.5}$ whilst the medium and large clods had a value of 4.36mm/day$^{0.5}$ and 3.04 mm/day$^{0.5}$ respectively.

5.3 Soil Tine Interaction Studies

5.3.1 Calibration of Dynamometer

Dynamometer test results shown graphically in Figures 5.21 and 5.22 demonstrated a linearity of response, independence of loading position and low cross sensitivity when subjected to different loading systems. For each of the results obtained, a single regression line was fitted. Results for channel Fx as shown in Figure 5.21a show that:

i) The output response was linear for various loads with a correlation coefficient of 0.9999 and a channel sensitivity of 0.38 µV/N/V .

ii) The error between the output of the response curves for the load positions x_o = 100 and x_o = 680 mm was 0.14% at 1001 N.

iii) The cross sensitivity resulting from force Fz (Table A5.35 in the Appendix) gives a maximum output of 150µV (equivalent to a load of 1.68 N) for a vertical load of 500 N. Using similar arguments that the angle of the resultant force is 20^0 (Payne and Tanner via Godwin, 1974) the corresponding force for a tine force system is 1374 N. Therefore the cross-sensitivity is0.12%. The variation of output with loading position for different loads is shown in Figure 5.21b.

Results of the Fz channel as shown in Figure 5.22a show that:

i) The output response was linear for all loads with a correlation coefficient of 0.9999 and a channel sensitivity of 0.413 μV/N/V .

ii) The cross-sensitivity of resulting force Fx (Table A5.36b in the Appendix) gives an output of 2.13 mV (equivalent load of 21.51 N) for a horizontal load of 1001 N. The corresponding vertical force is 364.33 N giving a cross-sensitivity of 5.9%.

Results of the My channel are shown in Figure 5.22b. The output shows linear response with a correlation coefficient of 0.9999 for the range of loads applied and a channel sensitivity of 5.92 μV/Nm/V.

5.3.2 Results of Single Tine Experiments

5.3.2.1 Nature of Soil Disturbance

The nature of soil disturbance was determined on a basis of visual observation, the movements of subsurface beads, soil heave and movements in a glass sided tank.

5.3.2.1.1 Visual Observation

From observations of the surface soil movement recorded on a cine-film during forward movement of the tines, a soil wedge in the shape of a rounded bulb was observed ahead of the tines. The size of this bulb was observed to be dependent on the tine width and rake angle and was continually being reformed by soil coming from depth as the tine travelled forward. The soil mass ahead of the forward inclined and vertical tines moved forwards and upwards without a distinct shear plane being developed similar to the failure observed by Lawrance (1978) and Stafford (1979) whilst the backward raked tine had very little upward movement. The uniform soil wedge or bulb built on the tine face was in accordance with earlier findings of Payne (1956), Payne and Tanner (1959) O'Callaghan and Farelly (1964) and later Godwin (1974). Hettiaratchi and Reece (1967) assumed the vertical wedge on the tine face displaced the soil sideways and backwards into the trench created by the tine.

At 45^0 rake angle and at shallower depths, a segment of soil flowed plastically upwards as the tine moved forward. It then fell to one side after travelling some distance with the tine. The appearances of the soil in front of the tine could be described as " boiling " from the soil mass. The soil was observed to flow laterally around the tine. The groove formed was rectangular, flat sided and smeared and its width was almost the same as tine width. Increasing working depth increased the amount of soil being moved upwards and the lateral extent of heave increased slightly. The side view of a 25.4 mm tine operating at 50.8 mm depth is shown in Plate 5.1 whilst

Plate 5.2 shows the wall of the slot cut by a 25.4 mm tine at 152.4 mm depth. For tines greater than 50.8 mm in width, very little side heave was visible regardless of depth of operation. Soil movement was mainly forward and upwards with a rectangular groove being left (Plate 5.3). At 42% moisture content, some tearing away of soil was observed near the soil surface. No cracks were observed at all depths in the walls of the tine groove unlike those noted by Lawrance (1978).

Disturbance at 90^0 rake angle, was similar to 45^0 rake angle with upward flow of soil and continuous bulging as the tine moved forward as shown in Plate 5.4. No shear planes were distinctly formed and soil tended to flow around the tine. For the wider tines above 50.8 mm, very little side heave occurred. Some tearing away of soil was also observed at 42% moisture content (Plate 5.5). For backward raked tines, little forward movement of soil was observed. Instead, the soil moved sideways with lateral heave being distinct particularly with increasing tine width. Some soil was noted to flow along the tine face as it travelled forward (Plate 5.6). No distinct shear planes were formed. Soil tended to flow around the tine and the groove formed was also rectangular. At greater depths, the soil tended to move into the groove. In all tests, the 135^0 rake angle tine created the greatest extent of lateral heave.

The implication of this failure is that there is little crescent soil failure which is required to cause soil loosening and the production of soil aggregates. Results from surface observation showed that much more soil was forced upwards and forwards by the 45^0 rake angle tine. The 90^0

rake angle tine caused some forward and upward soil movement but the sideway movement was greater compared to the forward raked tine. With the backward raked tine the sideway movement was predominant. The type of failure was of flow type as observed by Stafford (1979) and described by Hettiaratchi (1987). Profiles of soil disturbance for three depths at three moisture contents and at three rake angles were also determined. These are presented in Figures 5.23 to 5.30. Soil moving ahead of the tine was not collected and hence was not taken into account. Hence the total area of disturbance does not match the area of surface heave.

5.3.2.1.2 Soil Displacement Using Bead Tracer Technique.

Records of forward, upward and sideways displacement of soil by a 50.8 mm tine at three depths and mounted at three rake angles were obtained using beads and string implanted in the soil. For all rake angles, the trajectories of the implanted beads within the soil mass had forward, upward and sideways movements over the entire working depth as shown in Figures 5.31 to 5.33 although the forward movement was less with the backward raked tine. However, no shear plane was observed to rise to the soil surface. Bead movements again indicate that soil movement was greatest near the tine side and the forward raked tine moved the most soil upward and forward. The vertical tine caused some forward and upward movement of soil but the sideway movement was much greater than that of the forward raked tine. The backward raked tine had more sideways bead movement and almost no forward movement.

Soil displacement caused by the tine at different depths resulted in the formation of soil heave beyond the tine sides. The lateral extent and height of the heave depended upon tine rake angles. As soil was homogeneous and incompressible, no volume change within the soil mass was expected to occur. In the dry and heterogeneous situation, a reduction of soil volume would indicate soil compaction whilst an increase in soil volume indicate soil loosening.

Spoor and Fry (1984) studied the soil disturbance generated by 45° rake angle tine in a uniform sandy loam at 11% moisture content and observed that the shallow tine operating above its critical depth caused minimal disturbance beyond the major failure planes and the soil within the planes was effectively loosened. Working below critical depth, considerable soil disturbance was observed to occur beyond the failure planes near working depth with soil in that area being subjected to some compaction. In contrast, operating the 45° rake angle tine in a homogeneous clay soil at 70% moisture content, the soil at working depth of 152.4 mm experienced more upward and forward displacement nearer the tine side. Spoor and Fry (1984) further reported that compaction decreased as the soil surface was approached with a transition from net compaction to loosening. The transition depth moved closer to the soil surface as soil density decreased. The results of tine operating at 45° rake angle in a saturated clay show that soil compression concentrated throughout the working depth beyond the tine side. Since no beads were positioned nearer the soil surface, the nature of failure near the soil surface could not be compared.

However, at 42% moisture content, some tearing effect was observed near the soil surface.

5.3.2.1.3 Soil Displacement Using A Glass Sided Tank.

As explained earlier the purpose of the glass sided tank study using the talcum slurry technique was to supplement the results obtained by the bead tracer technique to indicate the nature of soil disturbance immediately ahead of the tine. Artificial soil was used since it was quite difficult to avoid wet clay soil sticking to the glass plate. A mixture of kaolin clay and Shell Carnea 21 oil (mineral based) was mixed to give the equivalent strength properties of 56% moisture content (dry basis) of the real clay soil used for the tine experiments. A moisture content of 56% was selected because the mixture was too soft to handle at an equivalent strength of 70% moisture content and too stiff to prepare in the tank when the equivalent strength was similar to 42% moisture content of wet clay. The strength properties measured using the triaxial test apparatus is presented in Figure 5.34. Samples for the triaxial tests were taken with a corer from a bucket packed with an artificial soil and then extruded and cut to length.

A preliminary run was conducted at a very slow speed to observe the failure pattern caused by the 12.5 mm tine at three rake angles at 101.6 mm depth. At 45^0 rake angle, the soil moved forward and upwards with soil continually moving from the base. The formation of soil wedge was not distinct as soil was moving continually upwards. However, no rupture plane was formed on the soil surface. Soil at the edge of the tine was observed to undergo some tearing frequently found in tensile failure. Cracks appeared along the side walls of the trench created by the tine. This condition could be due to the nature of the artificial soil which was less sticky, lacked the viscosity and felt spongy. It was also difficult to mix homogeneously and the boundary between layers would still be visible when two lumps of soil were pressed together. At 90^0 rake angle, the soil experienced some upward and forward movement without any rupture plane being formed. The 135^0 rake angle, on the other hand, experienced little or no upward soil movement on the soil surface. The movement of a large mass of soil ahead of the tine was observed as it moved through the soil.

Following from the above observation, the soil was again prepared to the required depth and tine moved through the soil, after a grid of talcum slurry was marked onto the side soil surface. Once the bulge of soil was visible on the soil surface, the carriage was stopped and the deformed grid was traced onto a transparent paper. This was repeated for all rake angles. The deformed grid patterns are presented in Figures 5.35 to 5.37. Results of the glass sided tank showed that soil was moved forward and upward with the forward raked tine. With the vertical tine, some forward and upward movement was observed. The formation of soil wedge was not distinct as the soil seemed to accumulate on the tine and moving continuously from the base. The backward raked tine created no upward movement but forward movement was greater. A large mass of soil was observed to form ahead of the tine as it moved forward.

5.3.2.1.4 Lateral Extent And Height of Soil Heave.

All tines raked at 45^0 and 90^0 rake angles produced heave ahead and to either side (lateral) whilst the backward raked tines produced mainly lateral heave. Heave gradually decreased with distance away from the side of tine. For all tine widths, the extent of lateral heave was greatest with the backward raked tines followed by the vertical and the least by the forward raked tines. The effects of tine rake angle on the magnitude of the extent of soil heave are shown in Figure 5.38.

At 42% moisture content, increasing rake angle increased the extent of heave for all tine widths at all depths. The rate of increase in the magnitude of the lateral extent is less between 45^0 and 90^0 degree rake angles than between 90^0 and 135^0. The relationship between the extent of heave and rake angle follows the trend shown by the relationship between draught force and rake angle. At 45^0 rake angle, soil moved more upwards and forward. At 90^0 rake angle, more soil was pushed sideways with some forward and upward movements whilst at 135^0 rake angle, sideways movement was predominant with very little upward soil movement from below the soil surface. A similar trend was shown with soils at 56% and 70% moisture contents. At 70% moisture content, the 101.6 and 152.4 mm tines caused little sideways movement at 45^0 rake angle. The soil flowed up and fell onto the surface after some travelling distance caused by the tine. Increasing the rake angle to 90^0 increased the magnitude of lateral movement slightly. At 135^0 rake angle, the soil experienced greater lateral movement.

increasing depth increased the extent of lateral heave. At 45^0 rake angle, the tines tended to behave more like a wide tine whereby soil movement was mainly pushed forward and upwards ahead of the tine and the magnitude of the extent of lateral heave was the lowest. At all rake angles, the 50.8 mm tine caused the largest extent of soil heave. However, the rate of increase in lateral heave was greatest for the wider tines when operated above 90^0 rake angles.

The effects of tine depth on the extent of heave for all moisture contents are given in Figure 5.39. At 45^0 and 90^0 rake angles, increasing tine depth from 50.8 to 101.6 mm increased the extent of heave at an increasing rate but beyond 101.6 mm depth, the rate of increase was smaller. At 135^0 rake angle, the increase was generally linear for both 25.4 and 50.8 mm tines tested. The smaller increase in the the extent of heave above 101.6 mm depth was due to more soil being moved forward and upwards with tines raked at 45^0 and 90^0 rake angles. With the backward raked tine, a static wedge was formed ahead of the tine which increased with the tine width. Soil ahead of this static wedge moved sideways as the tine moved forward with little or no upward soil movement.

The relationship between the extent of lateral heave and tine width is shown in Figure 5.40. At 45^0 and 90^0 rake angles lateral heave increases to a maximum when tine width increases from 25.4 to 50.8 mm but decreases at 101.6 mm and remains almost constant thereafter. At 135^0 rake angle, the heave did not decrease markedly as tine width increased beyond 50.8 mm. Instead the heave remained almost constant at both depths tested. The nature of soil failure was predominantly lateral.

The extent of heave was found to be greatest at 70% moisture content for all rake angles (Figure 5.41). The increase between 42% and 56% moisture contents is generally greater than between 56% and 70% moisture contents for 90^0 and 135^0 rake angles. At 45^0 rake angle, the increase was nearly linear with increasing moisture content. The possible reason for the largest extent of heave at 70% moisture content could be explained by the fluid mechanics of a thixotropic liquid which begins to dominate the disturbance effect as the liquid limit is approached (Massey, 1972). This disturbance must not be confused with the disturbance of brittle soil material. It is strictly thixotropic deformation where the soil attempts to transmit hydraulic pressure as a wave form but this is heavily damped by the thixotropic effect as distance increases from the tine. Therefore the surface disturbance develops characteristics of a frozen wave. A summary of the results for two tine widths is shown in Table 5.8 whilst Table 5.9 shows the side disturbance between four tine widths at two depths. Detailed measurements of the extent of heave for the three moisture contents are presented in Tables A5.37 to A5.42 in the Appendix.

Heights of heave at 70% moisture content for all rake angles, depths and tine widths are shown in Figure 5.42. The results confirm that at 45^0 and 90^0 rake angles, soil movement was greatest near the tine side and decreasing rapidly with distance. There was more lifting of soil resulting in more forward and upward movements than sideways for the forward inclined tine. The vertical tine caused some forward and upward movement but the sideways movement was slightly greater than the forward inclined tine. With the backward inclined tine, sideways movement was predominant resulting in greater lateral extent of heave but with a reduced height at a further distance from the tine side. The greater extent of heave laterally could be explained by the fact that further movement sideways would deform soil further upwards since the soil was incompressible. Further sideways movement would be restricted by the boundary conditions imposed by the walls of the soil tank. The effect of wider tines was to cause greater sideways movement since a greater mass of soil was pushed aside.

Based on the above results, it can be summarised that failure of wet soil was more of a flow type rather than brittle. No clearly defined slip planes were formed. Soil movement was greatest near the tine side decreasing rapidly with distance. Wedges were formed ahead of all tines and these forced soil ahead and sideways depending upon tine rake angles. With forward inclined tine, there was more upward and forward movement giving the lifting effect thereby reducing the sideways movement. Some upward and forward mpvements were observed with the vertical tine but sideways movement was much more in evidence. The backward raked tine had the largest sideways movement while greater mass of soil was pushed forward ahead of the tine. The height of lateral heave for the forward raked tine was greater and its lateral extent smaller compared to the vertical tine. The lateral extent of heave for the backward raked tine, however, was more extensive.

5.3.2.2 Draught Force

The effect of tine rake angle on draught force at different working depths and moisture contents is shown in Figure 5.43. Increasing rake angle increased the draught force curvilinearly on all widths of tine at all depths and all moisture contents. The increase in draught force between 45^0 and 90^0 rake angles for narrow tines was small but considerable beyond, the increase being more evident at greater working depths. With wider tines, the increase in draught force was greater.

The characteristic shape of the draught force versus rake angle curve was similar to that observed by Osman (1964), Payne and Tanner (1959), Tanner (1960), O'Callaghan and Farelly (1964) and Hettiaratchi and Reece (1967) in dry brittle soils. The increase in draught for the narrower tines was however less rapid between 45^0 and 90^0 rake angles compared to their results. The results differed from the observations of Stafford (1984), Omer (1977) and Lawrance (1978) in that their draught forces decreased with increasing rake angle. All used plane non-relieved tines, Stafford working in both a clay soil and in a plasticine mixture whilst Omer and Lawrance used a kaolin/oil mixture. The inverse relation between draught and rake angle could be due to the edge effects with non-relieved tines. With these tines at lower rake angles, the force generated by adhesion on the tine sides is considerably larger in a cohesive soil due to the bigger surface area in contact, than with a vertical tine. The artificial clay of Omer and Lawrance could be another factor contributing to the discrepancy as it lacked the natural flow and smoothness of a real soil. In fact, the kaolin mixture gave a spongy feeling and did not mix homogeneously when separate lumps were pressed into each other. When failed, it always gave the impression of a tensile failure. A summary of its properties is presented earlier in Figure 5.34.

The change in draught force between 45^0 and 90^0 rake angles for the narrower tines was not significant. The lower draught force exerted by the forward raked tine can be explained by the fact that more soil was being lifted upwards amd moved forward than pushed sideways. The vertical tine, on the other hand caused more sideways disturbance with some forward and upward soil movement. With lateral failure being more dominant, the pressure on the tine face is greater and hence increased the draught force. With the backward raked tines, bigger static wedges were formed and soil ahead was pushed mainly sideways. In a cohesive soil, the sliding resistance on the wedge sides contributed an additional force causing the total force acting on the backward tines to increase significantly. This force increased as tine width increased. The 135^0 rake angle tine also disturbed a much greater volume of soil.

The effect of tine depth on draught force for different rake angles at three moisture contents is shown in Figure 5.44. Increasing depth increased the draught force at all rake angles, the increase being greater with the wider tines. The curvilinear relationship between draught force and tine depth was similar to the results of Zelenin (1950) working with tines more than 10 mm wide in loam soil. Similar results in cohesive soils were also reported by O'Callaghan and Farelly (1964) and Wismer and Luth (1972).

The relationship between draught force and tine width is shown in Figure 5.45. Increasing tine width increased the draught force at all depths and at all rake angles. At 45^0 rake angle, the rate of increase was slightly greater with the narrower tines giving a parabolic relationship. At 90^0 and 135^0 rake angles, the relationship of draught force with tine width was linear. The parabolic increase in draught force with tine width at 45^0 rake angle was in accordance with laboratory observations in cohesive soils (Payne, 1956) and with the findings of Zelenin (1950). At 90^0 and 135^0 rake angles, the relationship was almost linear with width in accordance with the results observed by Payne and Tanner (1959). This correlates well with the observation that the lateral extent of heave increased with width particularly at 135^0 rake angle. As tine width increased, a greater volume of soil was moved and generating a bigger resistance. Increasing moisture content from 42% to 70% and hence decreasing shear strength (Figure 5.4) decreased the draught force of all tines with a hyperbolic relationship at all rake angles. The hyperbolic relationship was more evident at greater depths as shown in Figures 5.46 to 5.48. Statistically, all factors (rake angle, tine width and working depth) had a significant effect (at 95% confidence level) on draught force individually and in interaction with each other at all moisture contents.

5.3.2.3 Vertical Force

The relationship between vertical force and tine rake angle for each tine width is shown in Figure 5.49 for the three moisture contents. The vertical force increased curvilinearly upwards with increasing rake angle at all depths. For a given tine width and working depth, the greatest force was developed by the backward raked tine. The vertical force component was zero at approximately 65^0 to 70^0 acting upwards at greater rake angles and downwards at lower. This is consistent with an angle of soil metal friction of 20^0 to 25^0. The results are consistent with those of Omer (1977), Lawrance (1978), Wismer and Luth (1972), Godwin (1974), Osman (1964), Payne (1956) and Payne and Tanner (1959). The effect of tine depth upon the vertical force component for each tine width and rake angle is shown in Figure 5.50. There is a linear relationship between the magnitude of the vertical force component and tine depth for 90^0 and 135^0 rake angles. At 45^0, the relationship is slightly curvilinear at greater depths. For tines of given width, the force increased with depth, the rate of increase being greatest with the backward raked tine. The greater increase in vertical force with depth as experienced by the backward raked tine could be due to the increased soil mass being moved outwards and slightly upwards as the tine moved forward. The boundary effect within the soil tank may have contributed to some degree to the greater increase in vertical force component compared to forward raked and vertical tines.

The vertical force-tine width relationships illustrated in Figure 5.51, shows that the vertical force component for the 45^0 and 90^0 rake angles increases in magnitude with width but at a decreasing rate resulting in a parabolic relationship. At 135^0 rake angle, the increase is linear. The parabolic relationship is due to changes in the size of the deformed mass of soil with change in width. The greater increase in vertical force with width at 45^0 rake angle could be due to the large mass of soil that moved vertically over the tine surface as the tine moved forward compared to tines raked at 90^0. The adhesive component could have contributed additional force. The linear increase with width at 135^0 rake angle might be explained by the large mass of soil being deformed beneath the tine surface and bounded by the static wedge formed ahead of the tine and increasing proportionally with width. This movement could arise as a result of the boundary effect caused by the base and the walls of the soil tank. The base would restrict soil movement downwards causing it to flow outwards. As tine width increases, more soil would be pushed against the walls and in return additional pressure would be exerted by the walls onto the soil mass. As soil was incompressible, further sideways movement would cause the soil to move upwards.

Results on the relationship between vertical force and moisture content for each rake angle, tine width and depth are shown in Figure 5.52. The vertical force decreased parabolically with moisture content at 45^0 rake angle and hyperbolically at 90^0 and 135^0 rake angles. The reduction in the magnitude of the vertical force component is in accordance with the reduction in soil strength as soil moisture content increases. An analysis of variance at 95% confidence level showed that rake angle, tine width and tine depth have a significant effect on vertical force component individually and in interaction with each other. Forces for all tines, depths, rake angles and moisture contents are summarised in Tables 5.10 to 5.17. Detailed results are presented in Tables A5.43 to A5.48 in the Appendix.

5.3.2.4 Magnitude and Direction of the Resultant Force.

Increases in the draught and vertical force components at all rake angles were not proportional to tine depth increases and hence the direction of the resultant force changes as the aspect ratio (depth/width) changes. The direction of the resultant force calculated from the mean values of the force components is presented in Table 5.18 and shown graphically for all tests in Figure 5.53. The relationship is generally hyperbolic with a reduction in the angle of the resultant force as the aspect ratio increases apart from slight scatter at lower aspect ratios. The experimentally determined direction of the resultant force for tines with aspect ratios less than 6 are in accordance with those reported by Omer (1977), Payne and Tanner (1959) and Godwin (1974). The reduction in the angle of the resultant force with increasing aspect ratio could be due to a larger crescent-shaped zone being deformed by tines with small aspect ratio resulting in the angle of the resultant approaching the angle of soil metal friction. As the aspect ratio increases, the magnitude of the draught force increases at a greater rate than that of the vertical force component because of the effect of the purely lateral soil failure component. In the case of the backward raked tine, the vertical force component was much higher than the draught force component at greater depths. Since a static wedge was formed ahead of each tine and this increased with width, a greater mass of soil would be moved downwards and outwards increasing the vertical force component. This would be further compounded by the boundary effect. Increasing the aspect ratio would reduce the direction of the resultant force since outward flow of soil from beneath the tine would be less restricted thereby reducing the magnitude of the vertical force component.

5.3.3 Results of Multiple Tine Studies

5.3.3.1 Profile of Soil Disturbance

The soil disturbance created by the three tines at two moisture contents are presented in Figures 5.54 and 5.55. At the narrowest (101.6 mm) tine spacing, three slots were formed initially, but as the rear tine moved forward, the two outer slots were almost closed by the moving mass of soil being pushed by the rear tine. At 152.4 mm spacing, the two outer slots were not completely closed and at the widest spacing of 203.2 mm, the three tines were operating independently the slot width being similar to tine width. The profile of heave was more uniform at closer spacings than at wide. The uniform profile at the closer spacing was due to the meeting of the disturbance zones. At wider spacings, distinct formation of individual heaves was observed. There was little difference in surface disturbance between the leading tines acting shallower and at the same depth as the rear tine. At 56% moisture content, surface heave was less than at 70% moisture content. The profiles of disturbance caused by vertical interacting tines at 152.4 mm spacing with leading tines operating at two depths are shown in Plates 5.7 and 5.8.

The height of soil heave was also affected by tine spacing. As the spacing between interacting tines increased, the height of the heave of the disturbed soil in between the tines decreased. The maximum height of soil heave measured for the homogeneous soil condition was less than half the working depth of the tines when the leading tines were operated at the closest spacing (all tines at the same depth). Willatt and Willis (1965) as reported by Soomro (1976) obtained a higher soil heave in the field. The reason for this could be due to the heterogeneous soil condition where soil breakdown is normally determined by initial soil state and soil density which vary between surface and subsurface layers. In the drier condition, brittle failure would be prevalent. In a very wet condition where compressive failure is more dominant, the height and extent of heave formed would be restricted by the thixotropic properties of the soil which behaved more like a fluid as the saturation level increased towards 100%. In the context of soil puddling, soil water interaction would be better achieved by positioning the interacting tines at closer spacings since any water trapped in the slot initially created by the leading tines would be compressed into the soil mass. The magnitude of the draught force component would also be less at closer spacings. At wider spacings, soil water interaction to achieve the desired degree of puddle would be less effective since tines would only create vertical slots of the same width as the tine. Water trapped in the slot would not be squeezed completely since sideways movement of soil deformed by the adjacent tines would be limited by their distance apart. Therefore, more passes would be required incurring higher energy usage.

5.3.3.2 Magnitude of the Total Draught and Vertical Force Components.

The changes in draught and vertical force components for different tine spacings at both moisture contents are illustrated in Figure 5.56. Both the draught and vertical forces increased linearly with increasing tine spacing for both tine arrangements. Similarly both forces increased significantly when the leading tines were operated at the same depth as the rear tine. The small increase in the magnitude of the draught and vertical forces with increasing spacing indicates they are relatively insensitive to tine spacing. The increases corresponded to the extent of soil being deformed. Narrow spaced interacting tines tend to cause soil interaction closer to the tines with the rear tine moving into an already disturbed zone caused by the leading tines. At wider spacings, tines were operating independently and movement of soil sideways (lateral failure) would be less restricted. Regardless of further spacings, the extent of lateral failure zone would remain relatively the same below the critical depth, if any, with a tine raked at 90^0. Consequently, the magnitude of the draught force would theoretically remain the same or increase slightly. Comparison of forces between a single tine and multiple tines operating at the same depth shows a very significant difference in draught force indicating that there was little or no benefit when vertical interacting tines were used in very wet cohesive soil. Detailed measurements are presented in Tables A5.49 to A5.50 in the Appendix.

The total force exerted by the multiple tines presented in Table 5.19 for a given spacing was slightly lower than three tines working separately at the same depth. Some difficulty was faced when working at 56% moisture content when the greater resistance from the soil tended to bend the tines. This changed the rake angle to above 90^0 when working at greater depths resulting in much greater force. The spacing and depth of shallow leading tines are presented in Table 5.20. Based on the results, clearly there would be less benefit using multiple tines in a very wet and homogeneous condition apart from helping soil water interaction when positioned at closer spacings. Tables 5.21 and 5.22 give a comparison between single and multiple tines operated at two moisture contents.

5.4 Soil Puddling Experiments

5.4.1 Calibration of Wattmeter

The results on the calibration of wattmeter are presented in Figure 5.57. The relationship of the power output against speed was highly linear with a correlation coefficient of 0.9999. The motor used for the experiment required a 20 Watt of starting power before beginning to rotate.

5.4.2 Aggregate Size Distribution of Puddled Soil

Results on the percentage of aggregate breakdown are shown graphically in Figure 5.58. For a stirring time of five seconds, aggregates larger than 2.0 mm diameter constituted the largest percentage of total soil at 0.8 water-soil ratio but their number decreased sharply as the ratio was increased from 0.8 to 1.0. The decline in larger aggregates with increasing water-soil ratio corresponded with an increase in percentage of soil in aggregates of all other sizes. Beyond a water-soil ratio of 1.0, there was little further change. Table A5.51 in the Appendix show detailed results on the percentage of aggregate breakdown at different stirring times.

With a stirring time of 10 seconds the response to increasing water-soil ratio was similar to that of 5 seconds. The only exception in this case was that the percentage of soil in aggregates below 0.125 mm diameter was greater than that at 5 second stirring time. Increasing the stirring time to 20 seconds had little effect on aggregates in the size ranges from 0.125 to 2.0 mm over the different water-soil ratios. Aggregates below 0.125 mm continued to increase as those above 2.0 mm declined. An analysis of variance at 95% confidence level on the effect of stirring time and water-soil ratio on the percentage of soil aggregates below 0.5 mm diameter showed that both factors were significant individually and in interaction with each other. The results for soil aggregates below 0.5 mm diameter are shown graphically in Figure 5.59 and summarised in Table 5.23.

5.4.3 Bulk Density of Puddled Soil

The wet bulk density values of the puddled soil are shown in Figure 5.60. Wet bulk density values decreased steadily as the water-soil ratio was increased from 0.8 to 1.2 reaching an equilibrium state above 1.2. The response to increasing water-soil ratio with 10 second stirring time showed a similar trend. However, in this case, the density was slightly lower than that at the 5 second stirring time and the difference was significant at water-soil ratios above 0.8. Increasing the stirring time to 20 seconds had little effect on density beyond a water-soil ratio of 1.2. At a given water-soil ratio, increasing the stirring time decreased the wet bulk density values. An analysis of variance at 95% confidence level on the effect of stirring time and water-soil ratio on soil wet bulk density showed that both factors were significant individually and in interaction with each other. Detailed results are summarised in Table 5.24.

The results of the experiment conducted show that for a given energy input, aggregate breakdown could be increased and soil wet bulk density decreased by increasing the amount of water to a certain limit, beyond which there would be little further change. Water quantities above this limit would be wasted from a puddling point of view. For a given water-soil ratio, increasing the energy input would increase the aggregate breakdown and reduced the soil wet bulk density values. The reduction in soil wet bulk density with stirring time was due to the slower settling rate of the fine particles remaining in suspension. This increased the height of puddled soil and hence its volume at the time of measurement. The initial water level and the level of soil after puddling are shown in Table 5.25. These aggregates would have settled with time increasing the wet bulk density.

In the field situation, the amount of water required would depend on the initial state of the soil and the type of soil used. When a dry soil is suddenly and thoroughly flooded, its aggregates become saturated with water. The air in the soil pores is compressed by the advancing water until small air explosions occur causing the breakdown of larger aggregates or clods into smaller ones (Yoder, 1936; Henin and Santamaria, 1975; Russell, 1938; Robinson and Page, 1950; Mazurak, 1950; and Emerson and Grundy, 1954). The cohesion within soil aggregates decreases with increasing soil moisture contents. The individual aggregates become soft and may or may not disintegrate depending upon their stabilities. The stability of soil aggregates generally decreases with flooding because of swelling and increased solubility of some cementing agents (Sanchez, 1976; Marshall and Holmes, 1979; and Panabokke and Quirk, 1956). The magnitude of this phenomenon varies greatly with soil properties and water quality, ranging from little to almost complete aggregate breakdown. A series of studies conducted by Kawaguchi et al, (1956), Kawaguchi and Kita (1957) and Ahmad (1973) as cited by Sanchez confirmed that flooding gradually decreases aggregate stability because of organic matter decomposition and the reduction of iron and manganese oxide coats to soluble forms. Considerable amounts of water would be needed to overcome percolation and evaporation losses. The energy input,however, would depend on the degree of puddling required to create the necessary environment for rice root support and growth. Where energy is limited but water readily available, increasing the supply of water would be beneficial, but there would be little gain from using an excess. On the other hand, where energy is in abundance, the use of water could be reduced. Hence in soil puddling, there ought to be a balance between energy requirement and minimum water use. Further work is required to determine the efficiency of implements in varying soil conditions and water levels in the field before a conclusive recommendation could be made.

CHAPTER 6.0 FORCE PREDICTION MODELS

6.1 Introduction

In the past, there have been many attempts to model the behaviour of soil mathematically so that the soil forces generated by tine movement may be predicted. A review of mathematical solutions for calculating forces has already been described in Chapter 2.0. Some researchers notably Osman (1964), Siemens and Weber (1964) and Hettiaratchi et. al (1966) worked on wide tines (or blades). Payne (1956), O'Callaghan and Farelly (1964) and Hettiaratchi and Reece (1967) on the other hand worked on narrow tines whilst Zelenin (1950), Kostritsyn (1956) and Godwin and Spoor (1977) studied the mechanism of soil failure by very narrow tines. The soil failure patterns modelled in the earlier tine theories include the actual observed failure surface boundaries and simplified patterns involving both vertical and horizontal deformations. The experimental verification of the above theories has been limited to tests largely on soils at hard and friable consistencies or at the lower end of the plastic range where mainly brittle failure occurred. The exceptions to this are the works of Wismer and Luth (1972) who used dimensional analysis and Stafford (1979) who developed a mathematical model involving the operation of a rigid tine in a cohesive soil at various moisture contents and operating speeds. Stafford used his experimental results to derive some of the constants used in his model to calculate the forces. A fruitful approach to an understanding of the performance of agricultural tines appears to be the one that examines the action of such tines against the widely accepted theories of classical soil mechanics. This chapter describes an attempt to relate the findings of the study to a model or models based on Mohr-Coulomb soil mechanics parameters to describe the forces acting upon narrow and wide tines. The validity of the models was tested against the experimental results based on the mechanism of soil failure observed using the techniques described in Chapter 5.

6.2 Single Tine Experiments

6.2.1 Soil Failure Mechanism

From the experimental evidence based on observations during the passage of tines, three failure mechanisms were identified with tines of different rake angles. The 45^0 rake angle tine displaced the soil forward and upwards at all moisture contents with some soil movement sideways at higher aspect ratio (depth/width). At lower aspect ratio, the type of failure was purely two dimensional. At 42% moisture content some tearing effect on the soil surface was observed whilst at 56% and 70%, the tines were merely cutting slots as wide as the tine widths. No distinct shear planes were formed on the soil surface. Tensile cracks were also absent from the walls of the slot. In fact the slot walls were totally smeared. The vertical tine pushed soil upwards, forward and sideways similar to a three dimensional type of failure. However, no rupture plane was observed. With the backward raked tine, little upward soil movement was observed. Instead, the soil was pushed forward and sideways with a static wedge being formed on the face of the tine. A schematic diagram of tine inclination angles in the direction of travel is shown in Figure 6.1.

Based on the above observations, the following mechanics of soil failure appear to be possible:

a) For the forward and vertical rake angles, the tine acted as a retaining wall when it was wide with the result that when soil failure occurred the movement of the soil was in the vertical plane (upwards and forward). When the tine was narrow, the movement of the soil was in a horizontal plane with a soil wedge moving slowly upwards in a column along the face of the tine. The nature of soil failure was predominantly lateral. The second mechanism of soil failure was dependent upon the critical aspect ratio.

b) A backward raked tine, acted like a footing with a lateral type of failure more predominant for the range of tine widths and depths tested. The formation of an elliptical wedge (static soil zone) was apparent though not as distinct as that observed by Salokhe and Gee Clough (1988) with their lug studies in wet cohesive soil. The implanted beads not only moved sideways but also upwards from the base of the tine.

6.2.2 Development of the Force Prediction Models

The use of a general equation to represent all three rake angles was not possible due to the different soil failure patterns and this required a separate approach in developing the prediction models. These models were based upon the assumption that the soil worked by the tines obeys the Mohr-Coulomb failure criterion. It was assumed that the soil was homogeneous and isotropic and that inertia forces could be neglected. The assumed failure patterns for 45^0 and 90^0 rake angle tines are as shown in Figure 6.2 whilst Figure 6.11 shows the idealized failure pattern and the forces on a backward raked tine.

6.2.2.1 Soil Failure by Wide Tines (aspect ratio<1).

At 45^0 and 90^0 rake angles, the failure mechanism observed was purely two dimensional where soil nearer to the tine moved mainly upwards and forward. Based on this observation, use of a two dimensional soil failure model developed by Hettiaratchi and Reece (1974) was adopted. This prediction model, however, has the limitation in that the forces generated by the moving soil zone sliding along the slot walls are neglected. In cohesive soils, these sliding forces are significant as shown earlier by Zhang and Shao (1984) in their work on the dynamic performance of a single lug in wet clay soil. In predicting the total draught force, therefore, this sliding force component was added to the two dimensional model.

6.2.2.1.1 Failure Immediately Ahead of Tine.

Hettiaratchi and Reece (1974) have shown that the magnitude of the resisting force component per unit width of interface, P, can be computed from

$$P = \gamma z^2 K_\gamma + czK_{ca} + qzKq - (\gamma z^2 K_s e^{-s}) \qquad ......(6.1)$$

where

γ = soil dry bulk density

z = depth

c = soil shear strength

q = soil surcharge

s = soil effect

K_γ, K_{ca}, Kq, K_s = soil resistance coefficients (dimensionless number obtainable from charts).

Assuming zero surcharge and negligible soil effect, the above equation reduces to

$$P = \gamma z^2 K_\gamma + czK_{ca} \quad ....(6.2)$$

The actual value of tangential adhesion, A', per unit width, between soil and the tine interface is given by

$$A' = c_a z \operatorname{cosec} \alpha \quad ....(6.3)$$

where

c_a = soil-metal shearing resistance

z = depth

α = rake angle

The horizontal component, D_f, (or draught force) for the soil blade system is given by

$$D_f = (\gamma z^2 K_\gamma + czK_{ca}) \sin(\alpha+\delta) + c_a z \cot \alpha \quad ....(6.4)$$

and the vertical component, V_f, (or vertical force) is given by

$$V_f = -(\gamma z^2 K_\gamma + czK_{ca}) \cos(\alpha+\delta) + c_a z \quad ....(6.5)$$

where negative sign indicates the force generated by a vertical tine.

6.2.2.1.2 Failure at the Side of Tine.

The sliding resistance resulting from the forces generated by the soil zones against the furrow walls was determined by assuming that soil failure plane was inclined at $(45-\phi/2)^0$ to the surface and was linear from the base of the tine. The inclination of the surface of failure to the major principal stress depends only upon the soil's frictional properties and has the value $(45-\phi/2)^0$ (Terzaghi, 1942). In a saturated condition where ϕ is zero, the slip plane was assumed to be inclined at 45^0 with the horizontal. The idealized failure zone and the forces acting at failure for two rake angles are shown in Figure 6.3. The total sliding area for the two sides can be expressed as

$$2 \text{ Area ABC} = 2zmz0.5 = mz^2 \quad ....(6.6)$$

$$\text{The sliding resistance} = cmz^2 \quad ......(6.7)$$

where

c = soil shear strength

z = depth

m = rupture distance ratio.

Assuming the resultant of the sliding resistance component acts at angle δ to the normal to the tine, the horizontal and vertical components of the force can be represented by the following expressions:

$$H_s = mz^2\cos(\alpha-\delta) = mz^2 \sin(\alpha + \delta) \quad ....(6.8)$$

$$V_s = mz^2\sin(\alpha-\delta) = - mz^2 \cos(\alpha + \delta) \quad ....(6.9)$$

where H_s and V_s are the horizontal and vertical components of the resultant of the sliding resistance respectively. Combining equation (6.8) with equation (6.4), the general equation for total draught force, D_T, is given by

$$D_T = [\gamma z^2 K_\gamma + czK_{ca} + mcz^2]\sin(\alpha+\delta) + c_a z\cot\alpha \quad ....(6.10)$$

Similarly the general equation for total vertical force, V_T, can be expressed by

$$V_T = -[\gamma z^2 K_\gamma + czK_{ca} + mcz^2] \cos(\alpha+\delta) + c_a z \quad ..(6.11)$$

For the 45^0 rake angle, the horizontal component of the resultant of the sliding resistance acting at an angle δ to the tine interface can be expressed as

$$mcz^2 \cos(45-\delta) = mcz^2 \sin(45+\delta) \quad ......(6.12)$$

and the vertical component of the resultant of the sliding resistance is given by

$$mcz^2 \sin(45-\delta) = mcz^2 \cos(45+\delta) \quad ....(6.13)$$

Combining equation (6.12) with equation (6.4), the total draught force, D_T, for the 45^0 rake angle is given by

$$D_T = [\gamma z^2 K_\gamma + czK_{ca} + mcz^2] \sin(45+\delta) + c_a z \cot 45 \quad ..(6.14)$$

Similarly the total vertical force, V_T, can be expressed by combining equation (6.13) with equation (6.5) to give

$$V_T = [\gamma z^2 K_\gamma + czK_{ca} + mcz^2] \cos(45+\delta) + c_a z \quad ...(6.15)$$

For the 90^0 rake angle, the horizontal component of the resultant of the sliding resistance acting at an angle δ to the tine interface can be expressed as

$$mcz^2 \cos\delta = mcz^2 \sin(90+\delta) \quad ......(6.16)$$

and the vertical component of the resultant of the sliding resistance is given by

$$mcz^2 \sin\delta = -\,mcz^2 \cos(90+\delta) \quad ....(6.17)$$

Combining equation (6.16) with equation (6.4), the total draught force, D_T, for the 90^0 rake angle is given by

$$D_T = [\gamma z^2 K_\gamma + czK_{ca} + mcz^2) \sin(90+\delta) + c_a z \cot 90 \quad ......(6.18)$$

Similarly the total vertical force, V_T, can be expressed by

$$V_T = -[\gamma z^2 K_\gamma + czK_{ca} + mcz^2] \cos(90+\delta) + c_a z \quad .....(6.19)$$

The calculated results using the above models for the wide tine underpredicted the measured values for 45^0 and 90^0 rake angles by about 46% and 75% respectively. To improve this, the crescent effect was incorporated. This was thought reasonable because although distinct crescent failure planes were not observed, the crescent effect was manifest in the form of a heave around the tine. Godwin and Spoor (1977) had earlier described and modelled the failure boundary of the crescent in their narrow tine failure. In that model, it was assumed for simplicity that the crescent had a constant radius, r, given by

$$r' = f' = mz \quad .....(6.20)$$

where f' = forward distance

m = rupture distance ratio

z = depth of operation.

A more appropriate expression for the crescent boundary was later presented (Godwin et al., 1985) which gave better predictions. This was based on the work of Payne and Tanner (1959) which showed that for a range of tine rake angles and widths, under conditions where crescent failure is dominant, the magnitude of the lateral disturbance, s', is approximately equal to the working depth, z, of the tine. The crescent geometry and the crescent boundaries are shown in Figure 6.4. The radius of the crescent was expressed as

$$r' = f' - (f'-s')\sin^2\rho$$

$$= z[m-(m-1\ \sin^2\rho\ )] \qquad .....(6.21)$$

where s'= side disturbance

ρ = angle subtending the arc between forward distance and side disturbance.

Replacing the above equation in the horizontal component of their earlier force model and integrating between the limits $\rho = 0^0$ and $\rho = 90^0$, the draught and vertical force components can be expressed as

$$D_T = \{(\gamma z^2 K_\gamma + czK_{ca})[w+z(m-1/3(m-1))\}\sin(\alpha+\delta) + c_a z\cot\alpha + mcz^2\sin(\alpha+\delta) \quad ......(6.22)$$

$$V_T = -\{(\gamma z^2 K_\gamma + czK_{ca})[w+z(m-1/3(m-1))] + mcz^2\}\cos(\alpha+\delta) + c_a z ...(6.23)$$

where the sign is negative for a vertical tine. The improved model gave better prediction of the draught force values for the wide tine as presented in Tables A6.3. The vertical force results, however, were only close at 45^0 rake angle. At 90^0 rake angle, the model overpredicts the measured values as tine width increases beyond 50.8 mm.

6.2.2.2 Soil Failure by Narrow Tines(aspect ratio>1.0)

With narrow tines having an aspect ratio greater than 1.0, the soil can be considered to fail in a two dimensional manner in a horizontal plane. The idealized failure geometry for the narrow tines is as shown in Figure 6.5. The tine on passing through the soil forms a slot whose sides OF, O'F' form the free surfaces. For incompressible soil, it follows that the vertical soil wedge (assumed triangular with $\psi=45+\phi/2$) would be required to displace the soil sideways and backwards into the slot. The failure geometry compatible with these requirements is indicated by the curve ABEF where ABE is part of a logarithmic spiral centered at O and OEF is a plane shear zone necessitated by the free surface OF which is a principal plane. In reality the soil wedge moved upwards and the shape of the failure geometry would be more indicated by the curve ABE. Assuming rake angle has no significant effect on the direction of soil flow ahead of the soil wedge, this type of failure is similar to that of a deep narrow footing as described by Meyerhof (1951) and later adopted by Godwin and Spoor (1977) as a basis for their lateral failure theory for very narrow tine. The characteristic feature geometry for the lateral failure at higher aspect ratios is based upon the model expounded by Godwin and Spoor (1977) as shown in Figure 6.6. The resultant stress on the tine can be obtained from the Meyerhof (1951) solution given as

$$q_o = cNc' + p_oNq' + \gamma BN_\gamma'/2 \quad \ldots.(6.24)$$

where q_o = maximum vertical stress

p_o = $K_o\gamma z$ (magnitude of the geostatic stress from Godwin and Spoor, 1977).

K_o = (1-sinϕ)(ratio of the horizontal to vertical stress as given by Lambe and Whitman, 1945)

c = soil shearing resistance

γ = soil dry bulk density

B = footing width

Nc', Nq'= bearing capacity factors depending on the properties of ϕ.(Figure 6.7).

Since N_Y' is zero for ϕ=0 the total force Q on the tine face is therefore reduced to

$$Q = cNc'z + 0.5K_o\gamma Nq'z^2 \quad .....(6.25)$$

Assuming the interface as rough because of the cohesive nature of the soil, the resultant force is inclined at angle δ to the normal of the tine interface(Figures 6.8 and 6.9). The horizontal component of the force, is given by Q sin (α+δ) whilst the vertical component of the force can be expressed as Q cos (α + δ). In addition to the force generated by the soil ahead of the wedge, the side forces resulting from the rising soil wedge have to be considered. The total force resulting from the rising wedge can be expressed as wzc/cos45 where w is the width, z is the depth of tine and c is soil cohesion assuming the wedge is triangular with ψ=45+ϕ/2 and soil does not stick to the tine face. Resolving the resulting force acting on the wedge into horizontal and vertical components gives

$$H' = B'\cos\alpha \quad ......(6.26)$$

$$V' = B'\sin\alpha \quad ......(6.27)$$

where B'= wzc/cos45.

All the above equations can be reduced to one general solution for both rake angles and this is expressed as

$$Qh = w(cNc'z + 0.5K_o\gamma Nq'z^2)\ \sin\ (\alpha+\delta) + B\ \cos\alpha \quad .....(6.28)$$

and the total vertical force is given by

$$Qv = -w(cNc'z + 0.5K_o\gamma Nq'z^2)\ \cos\ (\alpha+\delta) + B\ \sin\alpha \quad ......(6.29)$$

where the sign is negative for vertical tine and positive for 45^0 rake angle tine. The total draught force caused by the 45^0 rake angle tine therefore can be expressed as

$$Qh = w(cNc'z + 0.5K_o\gamma Nq'z^2)\ \sin\ (45+\delta) + B\ \cos\ 45 \quad ....(6.30$$

and the total vertical force is given by

$$Qv = w(cNc'z + 0.5K_o\gamma Nq'z^2)\ \cos\ (45+\delta) + B\ \sin\ 45 \quad .....(6.31)$$

Similarly the total draught force caused by the vertical tine can be expressed as

$$Qh = w(cNc'z + 0.5K_o\gamma Nq'z^2)\ \sin\ (90+\delta) + B\ \cos\ 90 \quad .....(6.32)$$

and the total vertical force is given by

$$Qv = -\ w(cNc'z + 0.5K_o\gamma Nq'z^2)\ \cos\ (90+\delta) + B\ \sin\ 90 \quad ...(6.33)$$

The horizontal component of the force resulting from rising soil wedge is zero whilst the vertical component is given by wzc/cos 45.

6.2.2.3 Estimation of the Critical Aspect Ratio.

The use of the above two models has demonstrated that with a knowledge of the critical aspect ratio for a particular tine in a given soil condition, useful predictions can be made of the horizontal and vertical force component acting on tines of any width. With the limited experimental data, the transition point from lateral failure to upward failure is difficult to determine unless further experiments are carried out. However,if it is assumed that the soil ahead of the tine will fail along the path of least resistance in such a way that the horizontal force will be a minimum, then a numerical procedure can be used to determine the critical aspect ratio either by

(1) an iterative method where the magnitude of the horizontal force is determined for different assumed values of the critical aspect ratio or

(2) differentiation of the horizontal force function with respect to the aspect ratio and equating to zero.

The general equation for very narrow tine failure as proposed by Godwin and Spoor (1977) can be adapted to accommodate the aspect ratio term by converting the critical depth function. The fact that this model consists of two separate failure mechanisms is analogous to the two suggested failure mechanisms whereby the transition point is determined by the critical aspect ratio term. Converting the general equation presented in Godwin and Spoor (1977) for the horizontal force component and incorporating the crescent effect and the sliding resistance component, the resulting general equation in terms of aspect ratio can be expressed as

$$H = L + M + N + O + U + Q + G + W + T \quad .....(6.34)$$

where

$L = \gamma w^3 K_\gamma A_o^{\ 2} \sin(\alpha + \delta)$

$M = \gamma A_o^{\ 3} w^3 K_\gamma [m-1/3(m-1)] \sin(\alpha + \delta)$

$N = cw^2 Kca \sin(\alpha + \delta) A_o$

$O = cw^2 KcaA_o^{\ 2} [m-1/3(m-1)] \sin(\alpha + \delta)$

$U = c_a w^2 A_o \cot\alpha$

$Q = A_o^{\ 2} w^2 m \sin(\alpha + \delta)$

$G = w^2 cNc'(A - A_o) \sin(\alpha + \delta)$

$W = cw^2 (A - A_o) \cos\alpha / \cos 45$

$T = 0.5\ K_o \gamma w^3 (A - A_o^{\ 2}) Nq' \sin(\alpha + \delta)$

Similarly the vertical force component can be written as

$$V = U' +/- (L' + M' + N' + O' + T' + Q' + G' + W') \quad .....(6.35)$$

where

$L' = \gamma w^3 K_\gamma A_o^{\ 2} \cos(\alpha + \delta)$

$M' = \gamma A_o^{\ 3} w^3 K_\gamma [m-1/3(m-1)] \cos(\alpha + \delta)$

$N' = cw^2 Kca \cos(\alpha + \delta) A_o$

$O' = cw^2 KcaA_o^{\ 2} [m-1/3(m-1)] \cos(\alpha + \delta)$

$U' = c_a w^2 A_o$

$Q' = A_o^{\ 2} w^2 m \cos(\alpha + \delta)$

$G' = w^2 cNc'(A - A_o) \cos(\alpha + \delta)$

$W' = cw^2 (A - A_o) \sin\alpha / \cos 45$

$T' = 0.5 K_o \gamma w^3 (A - A_o^{\ 2}) Nq' \cos(\alpha + \delta)$

and the sign is negative for a vertical tine. Differentiating equation (6.34) with respect to critical aspect ratio and equating to zero yields the following equation:

$$3\gamma w^3 K_\gamma A_o^2[m-1/3(m-1)]\sin(\alpha+\delta) + \{2\gamma w^3 K_\gamma \sin(\alpha+\delta) + 2mw^2\sin(\alpha+\delta) + 2w^2 cKca[m-1/3(m-1)]\sin(\alpha+\delta)\}A_o + c_a w^2\cot\alpha - w^2 cNc' - cw^2\cos\alpha/\cos 45 - K_o\gamma w^3 Nq'\sin(\alpha+\delta) = 0 \quad ....(6.36)$$

The above resulting function is in the form of a quadratic where the critical aspect ratio is in the positive root of the equation

$$A_o = \frac{-b \pm\sqrt{b^2 - 4ac'}}{2a} \quad ....(6.37)$$

where $a = 3\gamma w^3 K_\gamma[m-1/3(m-1)]\sin(\alpha+\delta)$

$b = w^2\sin(\alpha+\delta)\{2\gamma wN_\gamma + 2cKca[m-1/3(m-1)] + 2m\}$

$c' = w^2[c_a\cot\alpha - cNc' - c\cos\alpha/\cos 45 - wK_o\gamma Nq'\sin(\alpha+\delta)]$

To estimate the forces acting on tines using equation (6.34), information on tine geometry, soil parameters and the rupture distance ratio is required. In the absence of rupture distance ratio for cohesive soil, data provided by Godwin and Spoor (1977) as shown in Figure 6.10 was assumed to give reasonable estimates to be used in the force prediction model. The main steps in the force calculation procedure can be summarised as follows

1. Determine the rupture distance ratio for the particular rake angle from chart.(Figure 6.10)

2. Determine K_γ, K_{ca}, for the appropriate values of α, ϕ and δ from charts given by Hettiaratchi and Reece (1974) or Hettiaratchi et al (1966). In the latter reference these are given as N values.

3. Determine Nc' and Nq' for the appropriate value of ϕ as shown in Figure 6.7.

4. Determine the sliding resistance component.

5. Determine the critical aspect ratio. If Ao > A, then wide blade theory with crescent effect considered is applicable. When Ao < A, the soil is considered to undergo lateral failure.

6. Substitute all parameters into equations (6.34) and (6.35) for the horizontal and vertical force components respectively. A computer programme to calculate both forces is given in Appendix C.

6.2.2.4 Backward Raked Tine.

Based upon the nature of soil failure observed during the passage of tines, the glass sided tank studies, the implanted beads and soil heave movements, a wedge of soil formed ahead of the tine moving forward and sideways. The movement of beads positioned beyond the tine side and wedge was sideways, forwards and slightly upwards. No distinct shear plane was evident. Based upon the elliptical shape of the mass of soil formed on the tine face, somewhat similar to that observed by Salokhe and Gee Clough (1988) and Zhang and Shao (1984), it is assumed that a model as shown in Figure 6.11 would be realistic for the soil failure pattern generated by the backward raked tine. This consists of an elliptical static soil zone with lateral failure ahead and beneath it separated by arc BC which is also assumed to exert a lateral failure force on the soil. The lateral failure is considered to behave in a purely two dimensional manner similar to a narrow footing. The arc BC has its limits at point B and C. Ahead of the tine the failure is assumed similar to a narrow footing orientated at 90^0 to the normally accepted direction of application (vertical plane). This soil failure mechanism is assumed to be similar to the lateral soil failure model as proposed by Godwin and Spoor (1977). Section AB is considered linear and positioned at half the tine depth for simplicity. In the real case this may be either underestimated or overestimated, depending on whether tine inclination is below or above 135^0. As very little soil moved upwards, the downward sliding force caused by the wedge is neglected.

The failure mechanism below the static soil zone is also considered to be similar to a narrow footing type of failure (horizontal plane). In saturated soil, the effect of soil weight is negligible because N_γ is zero. Soil surcharge was considered negligible since the stress caused by the surcharge was already considered in the lateral failure model generated by section AB and BC. Section CD was considered straight and its length equal to half the depth of tine as section AB. All forces were considered to act perpendicular to the pseudo-interface represented by the boundaries of the soil zone.

6.2.2.4.1 Lateral Force in the Vertical Plane (ahead of tine).

Since the failure mechanism ahead of section AB was assumed to be similar to the bearing capacity type of failure but orientated at 90^0 to the normally accepted direction of application, the lateral failure model of Godwin and

Spoor (1977) was adopted and this can be expressed as force Q1 given as

$$Q1 = cNc'z/2 + 0.5Ko\gamma z^2Nq'/4 + \gamma BN_\gamma'/2 \quad \text{........(6.38)}$$

where the second term represents the geostatic stress. The third term reduces to zero since N_γ' is zero for $\phi=0$.

6.2.2.4.2 Lateral Force, Q2, Below the Static Soil Zone.

The force Q2 resulting from lateral failure beneath the static zone was considered to be

$$Q2 = cNc'I + 0.5Ko\gamma I^2Nq' + \gamma BIN_\gamma'/2$$

$$= cNc'z/2 + 0.5Ko\gamma z^2Nq'/4 + \gamma BzN_\gamma'/4 \quad (\text{ since } I = z/2) \quad \text{..(6.39)}$$

Since N_γ' is zero for $\phi=0$, equation (6.39) therefore reduces to

$$Q2 = cNc'z/2 + 0.5Ko\gamma z^2Nq'/4 \quad \text{........(6.40)}$$

6.2.2.4.3 Lateral Force, Q3, of Arc BC.

Lateral force, Q3, caused by section BC can be obtained by integrating lateral force dq from 01 to 02. The force dq necessary to cause failure in sector d0 is given by

$$dq = cNc'dS + 0.5Ko\gamma(dS)^2Nq' \quad \text{...(6.41)}$$

where dS = (dS1 + dS2)/2, the effective length.

dS1 = R1d0, the length of arc BC

dS2 = R2d0, the length of arc B'C'

R1 = Radius of arc BC

R2 = Radius of arc B'C'

$R1 = x^2 + y^2 = 0.5z\sqrt{5}$ .....(6.42)

where $x = z$ and $y = 0.5z$

The difference between R2 and R1 (R2-R1) can be expressed as (w/2)tan45 assuming the wedge formed ahead of arc BC is triangular as shown in Figure 6.12. In saturated condition, angle MNO is 45^0. Therefore radius R2 can be expressed as

$$R2 = 0.5z\sqrt{5} + 0.5w$$
$$= 0.5\ (z\sqrt{5} + w) \quad ......(6.43)$$

Integrating force dq between angles 0_1 and 0_2 gives

$$Q3 = cNc'S_o + 0.5\gamma Ko(S_o^{\ 2})Nq' \quad ....(6.44)$$

where S_o is the effective length. Assuming force Q3 acts normal to the arc, the horizontal and vertical components of the force can be expressed as

$$Qh' = Q3 \cos 45 \quad .....(6.45)$$

$$Qv' = Q3 \sin 45 \quad ......(6.46)$$

6.2.2.4.4 Sliding Resistance Components on Both Sides and Beneath the Static Soil Zone.

A further component termed as the sliding resistance caused by the static zone was considered in the total force prediction model. This was considered necessary since the static soil zone was constrained to travel only in the forward direction and the force generated by the soil zone is considered significant since the soil was very cohesive. This sliding force is dependent upon the total area created by the static soil zone and soil shear strength. For simplicity the static soil zone was assumed to be triangular and the sliding area, SR, can be expressed as

$$SR = 0.5z^2 2 + wz$$

= sliding resistance caused by both walls of static soil zone and the sliding resistance beneath the static zone.

The total sliding resistance, SF, will be

$$SF = cz^2 + wzc$$

$$= cz(z+w) \quad \ldots\ldots(6.47)$$

where

c = soil shear strength

z = depth of tine

w = width of tine

The total horizontal and vertical force components for the backward raked tine resulting from equations (6.38), (6.40), (6.44) and (6.47) can be expressed as follows

$$H = wcNc'z/2 + 0.5Kow\gamma z^2Nq'/4 + [wcNc'S_o + 0.5w\gamma KoS_o{}^2Nq']\cos 45 +$$

$$cz(z+w) \ldots\ldots(6.48)$$

$$V = wcNc'z/2 + [wcNc'S_o + 0.5w\gamma KoS_o{}^2Nq'] \sin 45 \ \ldots\ldots \quad (6.49)$$

where H and V are the horizontal and vertical force components respectively.

6.3. Comparison Between the Predicted and Experimental Results.

The parameters used in the model evaluation are given in Table 6.1. The calculated and measured values of the draught and vertical forces for three moisture conditions are presented in Table A6.1 to A6.6 whilst the statistics of comparisons is shown in Table A6.7. A linear regression model was used to determine the association of the predicted force values with the experimental ones. Experimental and predicted force values were considered as x and y data points respectively. If there was 1:1 correspondence between x and y values, the regression coefficient and the intercept of regression line on y-axis would have the following values

$$y = a + bx$$

where b = 1.0 (regression coefficient)

a = 0.0 (intercept)

The letter r, in Table A6.7 is the correlation coefficient which when it approaches 1.0 gives an indication of close association between two data points.

In the statistics associated with Table A6.7, predicted values are compared with mean experimental force. From eighteen comparisons made, the regression coefficients of almost half of them were significantly different from 1.0, and eleven intercepts were significantly different from 0.0. In most cases, the values of the regression coefficient was greater than unity with an intercept less than zero, indicating that the model overpredicts the magnitude of the expected forces and in some cases underpredicts the magnitude of the expected forces.

Table A6.7 shows that generally the association between experimental and predicted values is very close for the draught force components at all rake angles for the range of moisture conditions tested. The vertical force component, however, is underpredicted at 45^0 and 135^0 rake angles but overpredicted at 90^0 rake angle and there appears to be significant difference between experimental and predicted values at 95% confidence limits for most of the comparisons except for 45^0 rake angle at 42% and 56% moisture contents. At 45^0 rake angle, the draught force values at 42% and 56% moisture contents were underestimated and for 70% moisture content, overestimated. This discrepancy could be due to changes in the soil parameters which have considerable effect in predictions. It appears that the model underpredicted the vertical force values at 70% moisture content. The absence of surcharge effect could contribute to the discrepancy resulting in a lower values than the measured ones. At 90^0 rake angle, both draught and vertical forces are overestimated and the difference between experimental and predicted values is significant at 95% confidence limits. The overestimation of the vertical force component occurs with tines with aspect ratio less than 1.0. This is the range of transition between wide tine failure and lateral failure where errors associated with the accurate prediction of critical aspect ratio as presented in Tables 6.2 to 6.4 could arise. The assumption of depth having the same magnitude as the lateral distance from the tine side may have contributed to the overprediction. In reality, the measured lateral distance from the tine side based on three random measurements along the path of tine was much smaller. The actual rupture distance ratio, m, could not be determined since no measurement was made on the distance of forward heave. The model for the backward rake angle tine predicts the draught force well at 70% moisture content but underestimates at 42% and 56% moisture contents. The vertical force values predicted are lower than the experimental ones. The association, between predicted and measured values, however, was close.

The goodness of fit between experimental and predicted values for selected rake angles and moisture contents are shown in Figures 6.13 to 6.15. The overall relationship between measured and predicted values for draught and vertical forces at different tine widths, rake angles, depths and moisture contents are illustrated in Figures 6.16 to 6.20. For comparison purposes between moisture contents, the 50.8 mm tine was selected since it represents the conventional narrow tine size used for soil cultivation. Wider tines were tested only at 70% moisture content. In general the shape and order of magnitude of the predicted draught curves show close agreement with the experimental data. With the exception of 90^0 rake angle for tines above 50.8 mm, the predicted vertical force components are in close aggreement with the experimental results.

6.4 Conclusion

Mathematical models have been developed to predict the forces acting on simple tines for application in the wet plastic conditions. The models take into account interface geometry and soil parameters. Validation of the models has been achieved using data from soil tank force measurements. Accuracy of predictions vary with tine rake angles and soil moisture conditions. In general the shape and order of magnitude of the predicted draught curves show close agreement with the experimental data. With the exception of 90^0 rake angle for tines above 50.8 mm, the predicted vertical force components are reasonably close with the experimental values.

CHAPTER 7.0 GENERAL DISCUSSION

7.1 Introduction

Various forms of soil manipulation are required in different field situations to change and improve soil conditions for the rice crop. These forms necessitate operations that will transform the soil into a level, uniform slurried condition with organic matter mixed in, a base of low permeability and of a high strength to minimise seepage and provide support and traction. Achieving this may involve breaking any clods present, increasing moisture content to reduce clod strength and form the puddle, mixing the organic material and soil smearing and compacting at depth. These conditions may have to be achieved under circumstances where either water or power resources are limited or in conditions where both factors may be restricted. The findings of the fundamental studies conducted are discussed below in the context of the above requirements.

7.2 Rate of Water Uptake and the Reduction in Clod Strength.

Wet clods are weak in strength and require less energy to break. Hence, the more rapidly high moisture contents can be achieved, the more efficient the soil breakdown and further mixing with soil organic matter. For timely operation, therefore, it is vital to have clods that can absorb water in the shortest possible time. This need is important especially in areas where water is scarce or the time to prepare land is short.

Results from the experimental studies have shown that small clods absorb water faster that larger ones indicating that they are more energy efficient in soil puddling than larger clods since the process of wetting and the weakening in strength is more rapid. Small clods, however, also tend to dry faster necessitating the shortest possible preparing time as compared to preparing the puddle from larger clods if water requirements are to be kept to a minimum. Greater weakening resulting in further breakdown through weathering is likely to happen where clods undergo rapid moisture changes if they are not sufficiently weak. Soil that are already wet and weak require very little additional water for clod breakdown, but may need some additional water to help scouring. Whatever the cost, delays in puddling should be avoided when preparing from small clods since it will set back the whole cropping schedule due to rapid water loss.

The studies have also shown that rapid water uptake is more evident with dry clods than the wet ones. At lower initial moisture content, clods are much more stronger and would benefit from wetting if energy is limited. With a shallow depth of water on clays, however, differential swelling effects during capillary rise are likely to decelerate water uptake on surface clods. On the other hand, when clods are more densely packed (confined state), water uptake is more rapid. Based on these findings, consolidation of surface clods could ensure rapid wetting and weakening of clods in conditions of wetting by capillarity. In the field situation, consolidation can be achieved by using implements that exert downward force. If tined implements are used, the backward raked tines would be the ideal choice though the draught force requirement would be high.

7.3 Initial Loosening.

In situations where the soil needs loosening before puddling, brittle failure is required. These studies showed that this is almost impossible to achieve with tines of whatever shape when the soil is in a plastic condition. Any such operation, therefore, needs to be conducted at lower moisture contents and any clods formed, should be reduced in size to enable rapid water uptake on wetting.

7.4 Soil Water Mixing.

The process of mixing soil with water is normally achieved by dispersing soil and breaking any clods further to enable rapid water uptake. Based on the studies, forward inclined tines help bring soil upwards but are not efficient tools at breaking clods and tend to move trash to the soil surface, though their unit draught force is low. Backward raked tines are good clod breakers but require higher draught force. The increase in draught force between 45^0 and 90^0 rake angle tines was small compared to the increase between 90^0 and 135^0 rake angles. This indicates that there exist a possibility of using the 90^0 rake angle tines as the optimum shape to churn soil in order to improve soil puddling without incurring greater loss in draught force. This finding also justifies the popular use of vertical tines in the traditional comb harrow commonly used in many rice growing countries. The concept of tines with adjustable inclination angles would appear to be a beneficial proposition especially for resource poor farmers. Tine inclination would be adjusted during the various stages of puddling.

In terms of energy usage, soil mixing with a single tine is not a viable proposition since it would require numerous passes. Multiple tine systems with closer spaced staggered tines would bring more soil to the surface as compared to wider spacings and are hence more efficient. However, unlike these combinations on dry soil, the leading tines do not reduce the draught on the rear tine. With backward raked tines, more soil would be moved sideways, generating greater soil water mixing as water trapped in the slots is further squeezed by the trailing tines. A system combining leading but forward raked tines with trailing but backward raked tines, staggered and closely spaced would increase the efficiency of soil mixing with reduced number of passes.

7.5 Burying of Organic Matter, Smearing and Panning at Depth.

The principal aim of this operation is to give a compact, low permeability layer at its base that minimizes percolation and supports field traffic. This necessitates implements that could readily penetrate the puddled layer, carry the organic material downwards and compact and smear at depth. Results of the experiments have shown that the backward raked tines are the best choice. However, they require large forces. Forward inclined tines increase the risk of excessive penetration and incorporate organic matter poorly. With multiple tine systems, closer spacing of backward raked tines would help further mixing, smearing and burying of the organic material beneath the puddled layer.

7.6 Smoothening and Levelling.

The levelness of the final surface condition depends on the uniformity of soil disturbance. This can be achieved using a wider backward raked blade. With multiple tine systems, the levelness of surface disturbance can be controlled by adjusting the tine spacing. Where complete disturbance is required, it is beneficial to use a multiple tine system at closer spacing. This would reduce the number of tine passes to complete the operation.

7.7 Soil Preparation With Powered Tools.

Implement forces and power requirements relate directly to initial soil conditions, deformation resistance, implement geometry, working depth and speed. The use of a powered tool in soil puddling has pointed to the fact that there ought to be a balance between energy input and water quantity used. Experiments on the effect of energy input and water consumption on soil puddling has shown that there is little benefit in increasing the amount of water beyond a certain limit for a given energy input. In cases where water is limited, the puddling process could be improved by increasing the input of mechanical energy. Additional water is needed only to overcome the scouring problem, if any.

CHAPTER 8.0 CONCLUSIONS.

8.1 Clod wetting and drying studies:

8.1.1 The amount of clod swelling on wetting increased with decreasing initial clod moisture content and clod size.

8.1.2 Clod water uptake on wetting by capillarity was significantly influenced by the surface confining stress on clod. At low confining stress, differential swelling caused horizontal cracks to develop near the base of the clod which disrupted capillary continuity and reduced water uptake. Surface loading of clods and hence increased confining stress, maintained continuity and caused faster wetting rate.

8.1.3 Larger clods required longer drying periods to achieve a uniform moisture profile within as compared to smaller clods. This was due to smaller surface area/unit volume.

8.1.4 The infiltration model based on linear heat flow into a solid (Carslaw and Jaeger, 1959), gave close predictions to the measured values for water movement into clods. Initial soil moisture content was found to dominate the rate of water uptake through its influence on hydraulic conductivity, diffusivity and sorptivity.

8.2 Puddling studies:

8.2.1 Within certain moisture limits, greater dispersion of soil particles could be obtained by increasing the energy input of a rotary puddler at a given soil moisture content. Similarly at a given energy input, increasing the soil moisture content increased the soil breakdown.

8.2.2 Beyond a certain moisture limit, increases in moisture content and or energy input, ceased to have any effect on soil breakdown. This limiting moisture content in these tests was significantly above (30%) the liquid limit.

8.3 Single tine studies:

8.3.1 Tines were not able to develop a brittle type of disturbance in wet clays at moisture contents within the central third (approximately) of the plastic range. If loosening is required before puddling, the operation needs to be conducted near or below the lower plastic limit.

8.3.2 Three types of soil disturbance were observed depending upon tine rake angle and aspect ratio. These were as follows:

8.3.2.1 With wider 45^0 and 90^0 rake angle tines having an aspect ratio of less than 1.0, the movement of soil was largely upwards and forward.

8.3.2.2 At greater aspect ratios when the tines were narrower and inclined at 45^0 and 90^0 rake angles, the soil moved forward and sideways with some soil moving upwards along the tine face. The sideways soil movement increased with increasing rake angle.

8.3.2.3 With backward inclined tines (135^0 rake angle), a static soil zone was formed on the face of the tine in the form of an elliptical wedge which pushed the soil ahead sideways and slightly upwards.

8.3.3 The extent of lateral heave increased with increasing moisture content in the upper part of the plastic range and with increasing rake angle.

8.3.4 Increasing tine rake angle increased the draught force curvilinearly upwards on all tines at all depth and moisture contents. The increase in draught between 45^0 and 90^0 was small, but considerable beyond 90^0..

8.3.5 The vertical soil force acting on the tine changed curvilinearly with changing tine rake angle. The vertical force component was zero at 65^0-70^0, acting upwards at higher rake angles but downwards below.

8.3.6 The relationship between the magnitude of the vertical force component and tine depth was linear with 90^0 and 135^0 rake angle tines but at 45^0, was slightly curvilinear.

8.3.7 The vertical force component for the 45^0 and 90^0 rake angles increased in magnitude with tine width but at a decreasing rate resulting in a parabolic relationship. At 135^0 rake angle, the increase was linear.

8.4.3 In the case of multiple tine systems, the draught and vertical forces increased linearly with increasing tine spacing. The rate of increase, however, was small.

8.4 Multiple tine studies:

8.4.1 No significant interaction in terms of soil disturbance occurred in multiple tine systems positioned at the same and different depths regardless of tine spacing. Each tine tended to create a slot.

8.4.2 The profile of soil heave formed was more uniform at closer tine spacings with the extent of heave decreasing slightly as the moisture content decreased in the mid plastic range.

8.4.3 The draught and vertical forces increased linearly with increasing tine spacing. The rate of increase, however, was small.

8.5 Mathematical modelling:

8.5.1 Soil mechanics models were developed based on the observed soil failure patterns which depended upon tine rake angle and aspect ratio on the assumption that the soil ahead of the tine would fail along the path of least resistance in such a way that the horizontal force would be a minimum. The models were as follows:

8.5.1.1 For the 45^0 and 90^0 rake angle and wide tines with aspect ratios less than 1.0, the existing two dimensional wide tine failure theory was adopted and modified to include the sliding resistance component at the side of the tine and the crescent effect as evidenced by the formation of soil heave near the tine sides.

8.5.1.2 For the 45^0 and 90^0 rake angle and narrow tines with aspect ratios greater than 1.0, the lateral soil failure theory was adopted and modified to include the rising soil wedge along the tine interface.

8.5.1.3 For backward inclined tines (135^0 rake angle), the lateral failure theory was modified to include the static soil wedge elliptical in shape, together with the sliding resistance components at the sides and beneath the wedge.

8.5.2 The prediction models developed on a basis of Mohr-Coulomb soil mechanics showed good agreement with the experimental results. At 90^0 rake angle, the vertical force values were underpredicted for tines greater than 50 mm wide. The association between the predicted and measured values was closest at 70% moisture content.

8.6 Practical applications:

From the viewpoint of soil puddling under circumstances where either water or power resources are limiting, the following conclusions could be drawn, based upon the fundamental studies conducted.

8.6.1 Small clods are more energy efficient when being broken down since the process of wetting and weakening in strength is more rapid.

8.6.2 Forward inclined tines would help bring soil upwards but are not efficient tools at breaking clods and tend to move trash to the soil surface. Their advantage is low unit draught.

8.6.3 Backward raked tines would be more efficient at mixing, clod breaking and smearing the puddled layer though a greater draught force is needed at any working depth and the large implement weights required to maintain a constant working depth.

8.6.4 The optimum rake angle range required to improve soil puddling with minimum draught force is near 90^0. For resource poor farmers, the concept of tines with adjustable inclination angle should be introduced where tine inclination could be adjusted during the various stages of soil puddling.

8.6.5 A multiple tine system combining leading forward inclined tines with trailing backward raked tines, staggered and closely spaced, would increase the efficiency of soil mixing, smearing and burying of organic material beneath the puddled layer with a reduced number of passes. Any water trapped in the slots initially created by the leading tines would be compressed into the soil mass.

8.6.6 In puddling with powered tools, there would be little gain in increasing the amount of water present much beyond the liquid limit for a given energy input. In cases where water is limiting, the puddling effect could be improved at a lower moisture content by increasing the mechanical energy input.

8.6.7 Field levelling could be better achieved with wide backward raked tines.

REFERENCES

Adair, C.R.; Miller, M.D. and Beachell, H.M. (1962)
Rice Improvement and Culture in the United States. Advances in Agronomy, Vol. 14, 61-108.

Agarwal, M.C.; Singh, R.; Batra, M.L and Agrawal, R.P. (1978)
Evaluation of Different Implements for Puddling of Rice Soils. RISO, Vol. 27 (4), 301-305.

Alderfer, R.B. (1950)
Influence of Seasonal and Cultural Conditions on Aggregation of Hagerstown Soil. Soil Sci. 69: 193-203.

Arya, L.M.; Farrell, D.A. and Blake, G.R. (1975)
A Field Study of Soil Water Depletion Patterns in Presence of Growing Soybean Roots. 1. Determination of Hydraulic Properties of the Soil. Soil Sci. Soc. Am. Proc., 39: 424-430.

Awadhwal, N.K. (1980)
Investigation of Dynamic Behaviour of Puddled Soil. Ph.D Thesis (Unpub.), Punjab Agricultural University, Ludhiana, India.

Awadhwal, N.K. and Singh, C.P. (1985)
Characterization of Puddled Soil. J.Agric. Engng. ISAE, Vol. 22 (1) 9-14.

Bates, W.N. (1957)
Mechanisation of Tropical Soils. Temple Press, London.

Baver, L.D. (1964)
Soil Physics. John Wiley and Sons, Inc., New York. Ed. 3, 148-149.

Beacher, B.F. and Strickling, E. (1955)
Effect of Puddling on Water Stability and Bulk Density of Aggregates of Certain Maryland Soils. Soil Sci. 80, 363-373.

Bekker, M.G. (1948)
Photographic Method of Determining the Soil Action Beneath Footings. Proc. 2nd Int. Conf. on Soil Mechanics and Foundations Engineering, Rotterdam.

Blake, G.R. (1965)
Bulk Density. In C.A. Black (Ed.), Methods of Soil Analysis, part 1. Agronomy 9. Am. Soc. of Agron., Madison, Wis. 374-390.

Bodman, G.B. and Rubin, J. (1948)
Soil Puddling. Proc. Soil Sci. Soc. Amer. 13:27-36.

Boyd, C.W. and Windisch, S.J. (1966)
A Technique for Measuring Deformations within a Sand under Controlled Wheel Loads. Proc. 2nd Int. Conf. of the International Society for Terrain-Vehicle Systems, Quebec.

Brady, N.C. (1978)
Soils and Rice. IRRI, Philippines.

Bruce, R.R. and Klute, A. (1956)
The Measurement of Soil Water Diffusivity. Soil Sci. Soc. Amer. Proc., 20: 458-462.

Carslaw, H.S and Jaeger, J.C (1959)
Conduction of Heat in Solids.
Oxford at the Clarendon Press.

Chisholm, T.S.; Porterfield, J.G. and Batchelder, D.G. (1970)
A Soil Bin Study of Three Dimensional Interference Between Flat Plate Tillage Tools Operating in Artificial Soil. Paper No. 70-122, ASAE, St. Joseph, Michigan, USA.

Chong, S.K. and Green, R.E. (1983)
Sorptivity Measurement and Its Application. In Advances in Infiltration. American Society of Agricultural Engineers, St. Joseph, Michigan, USA. 82-91

Davidson, J.M.; Nielsen, D.R. and Biggar, J.W. (1963)
The Measurement and Description of Water Flow through Columbia Silt Loam and Hesperia Sandy Loam. Hilgardia 34:601-617.

Day, P.R. (1965)
Particle Fractionation and Particle Size Analysis. In C.A Black (Ed.), Methods of Soil Analysis, part 1. Agronomy 9. Am. Soc. of Agron., Madison, Wis. 545-567.

De Datta, S.K.;Krupp, H.K.; Alvarez, E.I. and Modgal, S.C.(1973)
Water Management Practices in Flooded Tropical Rice. IRRI, Philippines. 1-18.

De Datta, S.K.; Morris, R.A. and Backer, R. (1978)
Land Preparation and Crop Establishment for Rainfed Lowland Rice. IRRI Res. Pap. Ser. 22 .

De Datta, S.K., Bolton, F.R. and Lin, W.L. (1979)
Prospects for Using Minimum and Zero Tillage in Tropical Lowland Rice. Weed Res. 19, 9-15.

De Datta, S.K. (1981)
Principles and Practices of Rice Production. John Wiley and Sons, New York.

Dettman, M.G. (1958)
Water Uptake by Pure Clays and Soil Crumbs. J. Soil Science Vol.9, 306-314.

Dinglinger, E. (1920)
The Resistance to Digging. Fordertechnik, Vol. 22.

Dransfield, P.; Willatt, S.T.; and Willis, A.H. (1964)
Soil to Implement Reaction with Simple Tines at Various Angles of Attack. J. agric. Engng. Res. 9 (3) 220-224.

Dutt, P., Panda, B.C. and Choudhury, A.K. (1986)
Float Harrow and Its Performance. Agricultural Mechanisation in Asia, Africa and Latin America, Vol. 17 (1) 37-38.

Ede, A.N. (1956)
Concrete as a Material for the Mechanical Installation of Land Drains. MSc. Thesis (Unpub.), University of Cambridge.

Elijah, D.L. and Weber, J.A. (1971)
Soil Failure and Pressure Patterns in Front of Model Tillage Tools. Trans. ASAE 14 (4) 781-785.

Emerson, W.W. and Grundy, G.M.F. (1954)
The Effect of Rate of Wetting on Water Uptake and Cohesion of Soil Crumbs. Journal of Agric. Science 44 (3) 249-253.

Emerson, W.W. (1955)
The Rate of Water Uptake of Soil crumbs at Low Suctions. Journal of Soil Science, Vol. 6, No. 1, 147-159.

Evans, D.E.; Johnson, C.E. and Schafer, R. L. (1984)
Tillage Tools:How Arrangement Affects Draft. Agric. Eng. 65 (10) 18-20.

Fagi, A.M. and De Datta, S.K. (1983)
Physical Properties of Rainfed Wetland Rice Soils as Affected by Cropping System and Crop Residue Management. Field Crops Research 6, 189-204.

FAO (1956)
Report of the Meeting of the Adhoc Working Group on the Problems of Mechanisation of Rice Production Under Wet Paddy Conditions. Rome, Italy.

Ferguson, W. (1970)
Some Draught Measurement of Scarifier Shares. J. agric. Engng. Res., 15 (2) 194-199.

Fountaine, E.R. (1954)
Investigation into the Mechanism of Soil Adhesion. J. Soil Sci. 5, 251-263.

Gardner, W.R. (1959)
Solution of the Flow Equation for the Drying of Soils and Other Porous Media. Proc. Soil Sci. Soc. Am., 23, 183-187.

Ghildyal, B.P. (1969)
Soil Compaction-A New System of Rice Cultivation. Indian Farming, Vol.X1X, NO.1, 19-24.

Ghildyal, B.P. (1978)
Effects of Compaction and Puddling on Soil Physical Properties and Rice Growth. Soils and Rice. 317-336.

Gill, W.R. and Vanden Berg, G.E. (1968)
Soil Dynamics in Tillage and Traction. ARS Handbook No. 316 USDA.

Godwin, R.J. (1974)
An Investigation Into the Mechanics of Narrow Tines in Frictional Soils. PhD. Thesis (Unpub.), University of Reading, UK.

Godwin, R.J. (1975)
An Extended Octagonal Ring Transducer for Use in Tillage Studies. J. agric. Engng. Res. 20 (4), 347-352.

Godwin, R.J. and Spoor, G. (1977)
Soil Failure with Narrow Tines. J. agric. Engng. Res., 22 (3), 213-228.

Godwin, R.J.; Spoor, G. and Soomro, M.S. (1985)
The Effect of Tine Arrangement on Soil Forces and Disturbance. J. agric. Engng. Res. 30, 47-56.

Grist, D.H. (1953)
Rice. Longmans, London.

Gumbs, F.A. and Warkentin, B.P. (1972)
The Effect of Bulk Density and Initial Water Content on Infiltration in Clay Soil Samples. Soil Sci. Soc. Amer. Proc., 36: 720-724.

Gumbs, F.A. and Warkentin, B.P. (1976)
Bulk Density, Saturation, Water Content and Rate of Wetting of Soil Aggregates. Soil Sci. Soc. Amer. Proc., Vol. 40 (1) 28-33.

Gupta, R.P. and Staple, W.J. (1964)
Infiltration into Vertical Columns of Soil under a Small Positive Head. Soil Sci. Soc. Amer. Proc. 28: 729-732.

Haines, W.B. (1923)
The Volume Changes Associated with Variation of Water Content in Soil. J. Agric. Sci. 13, 296-310.

Hanamoto, B. (1957)
Artificial Soils for Laboratory Studies in Land Locomotion. Land Locomotion Research Branch, OTAC, 20.

Hanks, R.J. and Bowers, S.A. (1962)
Numerical Solution of the Moisture Flow Equation For Infiltration Into Layered Soils. Soil Sci. Soc, Amer. Proc., 26:530-535.

Hansbo, S. (1957)
A New Approach to the Determination of the Shear Strength of Clay by the Fallcone Test. Royal Swedish Geotechnical Institute Proc. 14, Stockholm.

Harris, R..F; Chesters, G. and Allen, O.N. (1966)
Dynamics of Soil Aggregation. Adv. in Agronomy, 18, 107-169.

Harrison, W.L. (1973)
Soil Failure under Inclined Loads. J. Terramechanics, 10 (1), 11-50.

Have, H. ten (1967)
Research and Breeding for Mechanical Culture of Rice in Surinam. Centre for Agricultural Publications and Documentation, Surinam.

Have, H. ten (1972)
Cultural Practices for High Yields from Transplanted Rice. Indian Farming, 22 (4), 9-13.

Head, K.H. (1980)
Manual of Soil Laboratory Testing. Vol.1 Soil Classification and Compaction Tests. Pentech Press Limited, London.

Heard, H.C. (1960)
Transition from Brittle to Ductile Flow in Solenhofen Limestone as a Function of Temperature, Confining Pressure and Interstitial Fluid Pressure. Rock Deformation: Geological Society of America Memoir 79, 193-226.

Henin, S. and Santamaria, R. (1975)
Observation Comparee sur le comportment des fragments de terre soumis a l'action de l'eau de differentes solutions et de l'alcohol. Science du Sol. 171-182.

Hettiaratchi, D.R.P.; Witney, B.D. and Reece, A.R. (1966)
The Calculation of Passive Pressure in Two Dimensional Soil Failure. J. agric. Engng. Res., 11 (2) 89-107.

Hettiaratchi, D.R.P. and Reece, A.R. (1967)
Symmetrical Three Dimensional Soil Failure. J. Terramechanics. 4 (3) 45-67.

Hettiaratchi, D.R.P. (1969)
The Calculation of Passive Earth Pressure. PhD. Thesis (Unpub.), University of Newcastle-Upon-Tyne.

Hettiaratchi, D.R.P. and Reece, A.R. (1974)
The Calculation of Passive Soil Resistance. Geotechnique, 24(3), 289-310.

Hettiaratchi, D.R.P. and Reece, A.R. (1975)
Boundary Wedges in Two Dimensional Passive Soil Failure. Geotechnique, 25, 197-220.

Hettiaratchi, D.R.P. (1987)
A Critical State Soil Mechanics Model for Agricultural Soils. Soil Use and Management, Vol. 3, No. 3, 94-105.

Holmes, J.W. (1955)
Water Sorption and Swelling of Clay Blocks. J. Soil Sci. 6, 200-208.

Ichiba, S.; Hyodo, K. and Ooishi, Y. (1987)
Visualization of the Cutting Mechanism of Soils by the X-ray Radiography. Proc. 9 th Int. Conf. of Int. Society for Terrain Vehicle Systems, Barcelona, Spain, Vol.2, 793-800.

Izumi, S (1966)
Plowing, Puddling and Transplanting. In Matsubayashi et al.(eds), Theory and Practice of Rice Culture, second edition, Ministry of Agriculture, Japan. 379-396.

Jaky, J. (1948)
On the Bearing Capacity of Piles. Proc. 2nd Int. Conf. on Soil Mechanics and Foundation Engng.

Jamil, M.B. (1966)
Review of World Rice Industry. Proc. of Conference on Mechanisation and the World's Rice.
FAO, Rome, Italy.

Jarvis, N.J. and Leeds-Harrison. (1987)
Modelling Water Movement in Drained Clay Soil, 1. Description of the Model, Sample Output and Sensitivity Analysis. Journal of Soil Science 38, 487-498.

Jayasekara, E.H.W. (1966)
Proc. of a Symposium on Research and Production of Rice Varieties and Cultural Practices in Ceylon. The Columbo Apothecaries Ltd. Ceylon.

Johnson, L. (1963)
Power Requirement in Rice Production. Paper Presented at a Conference on Agricultural Engineering Aspect of Rice Production, IRRI, Philippines.

Johnson, G.C. (1977)
A Study of Abrasive Wear on Tines. MSc. Thesis (Unpub.), NCAE.

Kar,S., Varade, S.B., Subramanyam, T.K. and Ghildyal, B.P (1976)
Soil Physical Conditions Affecting Rice Root Growth: Bulk density and Submerged Soil Temperature Regime Effects. Agronomy Journal. Vol. 68, Jan-Feb. 23-26.

Kawaguchi, K. and Kyuma, K. (1977)
Paddy Soils in Tropical Asia : Their Material Nature and Fertility. The Univ. Press, Honolulu, Hawaii.

Keen, B.A. (1931)
The Physical Properties of the Soil. Longmans, Green and Co., London.

Kemper, W.D. and Koch, E.J. (1966)
Aggregate Stability of Soils From Western United States and Canada. US Dept. Agr. Tech. Bull. No 1355.

Khan, A.U. (1975)
Mechanization Technology for Tropical Agriculture. Agricultural Mechanization in Asia, Africa and Latin America, Vol. 6 (1), 30-35.

King, D.W. (1969)
Soils of the Luton and Bedford District-A Reconnaisance Survey. Soil Survey of England and Wales, Harpenden.

Klute, A. (1972)
The Determination of the Hydraulic Conductivity and Diffusivity of Unsaturated Soils. Soil Science Vol. 113, No. 4, 264-276.

Koenigs, F.F.R. (1961)
The Mechanical Stability of Clay Soils as Influenced by the Moisture Conditions and Some Other Factors. PhD Thesis (Unpub.) Wageningen, Netherland.

Koenigs, F.F.R. (1963)
The Puddling of Clay Soils. Netherland J. of Agric. Science. Vol.11, No.2 Special Issue, 145-157.

Komori, S. (1974)
Analysis of Labour for Mechanised Working on Paddy Field. Jap. Agric. Res. Quarterly Vol.8(3) 150-152.

Konaka, T. (1974)
Similitude Studies on Soil Dynamics Properties in Puddling Field. Japan agric. Research Quarterly, Vol.8 part 1, 37-39.

Korayem, A.Y. (1966)
Frictional Properties of Artificial Soils. Trans. of the ASAE. 145-146, 150.

Kostritsyn, A.K. (1956)
Cutting of a Cohesive Soil Medium with Knives and Cones. (NIAE Translation No. 58).

Kuether, D.O. and Duff, B. (1981)
Energy Requirement for Alternative Rice Production Systems in the Tropics. S.A.E paper, No. 790837, 1-11.

Kumar, A.; Patil, V.S and Krishnamurthy, K. (1977)
Water Requirements for Land Preparation. J. Current Research, Vol.6 Part 12, 212-213.

Kung, P. and Attayodhin, C. (1968)
Water Requirements in Rice Production. Proceeding Paper, 4 th Seminar on Economics and Social Studies, Los Banos, Philippines. 94-112.

Lambe, T.W. and Whitman, R.V. (1969)
Soil Mechanics. John Wiley and Sons; Inc., New York.

Lauritzen, C.W. and Stewart, A.J. (1941)
Soil-Volume Changes and Accompanying Moisture and Pore Space Relationships. Soil Sci. Soc. Am. Proc. 6, 113-116.

Lauritzen, C.W. (1948)
Apparent Specific Volume and Shrinkage Characteristics of Soil Materials. Soil Sci. 65, 155-179.

Lawrance, S. (1978)
Failure, Displacement and Compaction of Cohesive, Plastic Soil About Tines of Different Geometries. MSc. Thesis (Unpub.), NCAE

Lyon, T.L., Buckman, H.O., and Brady, N.C. (1952)
The Nature and Properties of Soils. 5 th Edition, Macmillan and Co., New York.

Marshall, T.J. and Holmes, S.W. (1979)
Soil Physics. Cambridge University Press.

Massey, B.S. (1972)
Mechanics of Fluids. Van Nostrand Reinhold Company Ltd., London.

Matsubayashi, M. (1968)
Theory and Practice of Growing Rice. Fuji Publishing Co. Ltd., Tokyo, Japan.

May, J. (1968)
Soil Mechanics and Dynamics Applied to Earth Moving. MEXE Technical Note No. 14, 167.

Mazurak, A.P. (1950)
Effect of Gaseous Phase on Water Stable Synthetic Aggregates. Soil Sci. 69: 135-148.

Mc Intyre, D.S. and Loveday, J. (1968)
Problems of Determination of Soil Bulk Density and Moisture Properties From Natural Clods. Soil Sci. 105: 232-236.

Mc George, W.T. (1937)
Studies on Soil Structure; Some physical Characteristics of Puddled Soils. Arizona Univ. Agr. Expt. Sta., Tech. Bull. No.67, 127-177.

Mc George, W.T. and Breazeale, J.F. (1938)
Studies on Soil Structure: Effect of Puddled Soils on Plant Growth. Univ. of Arizona College of Agriculture Agric. Exp. Station Technical Bulletin No. 72.

Mc Kyes, E. and Ali, O.S. (1977)
The Cutting of Soil by Narrow Blades. Journal of Terramachanics, 14, 43-58.

Meyerhof, G.C. (1951)
The Ultimate Bearing Capacity of Foundations. Geotechnique, No.2 (4), 310-332.

Miller, P.C.H. (1971)
Soil Failure and the Nature of the Force System with Very Narrow Tines. B.Sc Dissertation (Unpub.), NCAE.

Miller, E.E. and Gardner, W.H. (1962)
Water Infiltration into Stratified Soil. Soil Sci. Soc. Amer. Proc. 26 : 115-119.

Millington, R.J. and Quirk, J.P. (1959)
Permeability of Porous Media. Nature, Lond. 183, 387-388.

Moomaw, J.F. and Curfs, H.P. (1971)
Some General and Particular Aspects of Rice Soil Tillage. FAO Meeting of Experts on the Mechanisation of Rice Production and Processing. Rome, Italy.

Naphade, J.D. and Ghildyal, B.P. (1971)
Effect of Puddling on Physical Properties of Rice Soil. Ind. Journal of Agricultural Science 41 (12) 1065-1067.

Navasero, N.C. (1969)
A Row Seeder for Lowland Rice Soils. Saturday Seminar, Agric. Eng. Dept.
IRRI, Philippines.

Nichols, G. (1976)
Comparative Performance of the Howard, Dondi and Iseki Rotary Tillers. Muda Agric. Development Authority.

Nichols, M.L. and Reaves, C.A. (1958)
Soil Reaction to Subsoiling Equipment. Agric. Engng. St. Joseph, Michigan. V 39 No.6, 340-343.

Nijhawan, S.D. and Olmstead, L.B. (1947)
The Effect of Sample Pretreatment upon Soil Aggregation in Wet Sieve Analysis. Soil Sci. Soc. Amer. Proc. 12 : 50-53.

O'Callaghan, J.R. and Mc Cullen, P.J. (1965)
Cleavage of Soil by Inclined and Wedge Shaped Tines. J. agric. Engng. Res., No.10 (3), 248-254.

O'Callaghan, J.R. and Farelly, K.M. (1964)
Cleavage of Soil by Tined Implements. J. agric. Engng. Res., 9 (3) 259-270.

Ojeniyi, S.O. and Dexter, A.R. (1979)
Soil Factors Affecting the Macrostructures Produced by Tillage. Trans. of the ASAE.V 22 No.2, 339-343.

Olsen, H.W. (1960)
Hydraulic Flow Through Saturated Clays. Clay Mineralogy. 9: 131-161.

Olson, D.J. and Weber, J.A. (1965)
Effect of Speed on Soil Failure Pattern in Front of Model Tillage Tools. SAE Milwaukee Meeting. Paper No. 650691.

Omer, A.B. (1977)
Narrow Tines Failure of Cohesive Soils. MSc. Thesis (Unpub.), NCAE.

Osman, M.S. (1964)
The Mechanics of Soil Cutting Blades. J. agric. Engng. Res., 9 (4) 313-328.

Owen, G.T. (1988)
Soil Disturbance Associated With Deep Subsoiling in Compact Soils. Can. Agric. Engng. V 30 No.1, 33-37.

Painuli, D.K.; Woodhead, T. and Pagliai, M. (1988)
Effective Use of Energy and Water in Rice-Soil Puddling. Soil Tillage Res., 12:149-161.

Panabokke, C.R. and Quirk, J.P. (1957)
Effect of Initial Water Content on Stability of Soil Aggregates in Water. Soil Sci. 83, 185-195.

Pandey, K.P. and Ojha, T.P. (1970)
Optimum Shape of Rigid Traction Wheels for Puddled Soil Condition. J. agric. Engng. IIT, Kharagpur, 7 (1)

Pandya, A.C. (1962)
Irrigation of Rice. Indian Institute of Technology, Kharagpur.

Payne, P.C.J. (1956)
The Relationship Between the Mechanical Properties of the Soil and the Performance of Simple Cultivation Implements. J. agric. Engng. Res., 1(1) 23-50.

Payne, P.C.J. and Tanner, D.W. (1959)
The Relationship Between Rake Angle and the Performance of Simple Cultivation Implements. J. agric. Engng. Res., 4(4), 312-325.

Perumpral, J.V.; Grisso, R.D. and Desai, C.S. (1983)
A Soil Tool Model Based on Limit Equilibrium Analysis. Trans. ASAE, 26: 991-995.

Peynircioglu, H. (1948)
Test on Bearing Capacity of Shallow Foundations on Horizontal Top Surfaces of Sandfills and the Behaviour of Soils Under Such Foundations. Proc. 2nd Int. Conf. on Soil Mechanics and Foundations Engineering, Rotterdam.

Philip, J.R. (1957a)
The Theory of Infiltration: The Infiltration Equation and Its Solution. Soil Sci. 83, 345-357.

Philip, J.R. (1957b)
Numerical Solution of Equations of the Diffusion Type With Diffusivity Concentration Dependent. Aust. J. Phys. 10, 29-42.

Philip, J.R. (1968)
Kinematics of Sorption and Volume Change in Clay Colloid Paste. Aust. J. Soil Res., 6, 249-267.

Prandtl, L. (1920)
The Hardness of Plastic Bodies. Nachr. kgl. Ges. Wiss., Gottingen, Math. Phys. Klesse.

Prihar, S.S., Khera, K.L, Gajri, P.R. (1976)
Effect of puddling with Different Implements on the Yield of Paddy and Water Expense. Journal of Research, Volume xiii, No.3, 249-254.

Rajaram, G. (1987)
Force-Time Behaviour of Tine Implements. Master of Engineering Thesis (unpub.) Asian Institute of Technology, Bangkok, Thailand.

Rathje, J. (1932)
The Cutting of sand. Engineering 134, 116-118.

Rawlins, S.L. and Gardner, W.H. (1963)
A Test of the Validity of the Diffusion Equation for Unsaturated Flow of Water. Soil Sci. Soc. Amer. Proc. 27 : 507-510.

Reaves, C.A. (1966)
Similitude of Plane Chisels in Artificial Soils. Trans. of the ASAE. Vol. 9 No.2, 147-150.

Reece, A.R. (1965)
The Fundamental Equation of Earthmoving Mechanics. Proc. Symp. Earthmoving Machinery, Instn. Mech. Engrs. Pt.3E.

Richards, L.A. (1947)
Pressure Membrane Apparatus: Construction and Use. Agr. Eng. 28:451-454, 460.

Richharia, R.H. and Subbiah Pillai, S.M. (1962)
Mechanising the Puddling of Rice Lands. Proc. of the IAE, Vol.18, 23-24.

Richharia, R.H. and Pradhan, S.N. (1966)
Mechanised Puddling of Rice Lands. Proc. Conference on Mechanisation and the World Rice.,Warwickshire.

Robinson, D.O. and Page, J.B. (1950)
Soil Aggregate Stability. Soil Sci. Soc. Amer. Proc., 25-29.

Robinson, L.H. (1959)
Effect of Pore and Confining Pressure on the Failure Process in Sedimentary Rocks. Colorado School of Mines. Quarterly 54, 177-199.

Rogowski, A.S., Moldenhauer, W.C. and Khirkham, D. (1968)
Rupture Parameters of Soil Aggregates. Am. Soc. Soil Sci. Proc., Vol. 32 (5) 720-724.

Roscoe, K.H., Arthur, J.R.F. and James, R.G. (1963)
The Determination of Strains by An X-Ray Method. Civ. Eng. Pub. Works Rev. 58, 873-876, 1009-1012.

Rowe, R.J. and Barnes, K.K. (1961)
Influence of Speed on Elements of Draft of a Tillage Tool. Trans. of the ASAE, 4 (1) 55-57.

Russell, E.W. (1938)
Soil Structure. Imp. Bur. Soil Sci. Tech. Commun. 37.

Russell, E.W. (1971)
Soil Structure: Its Maintenance and Environment. J. Soil Science Vol.22 (2) 137-151.

Russell, M.B. (1985)
Rice Soil Physics and Agrohydrology. IRRI, Philippines.

Salih, R.O. and Maulood, A.O. (1988)
Influence of Temperature and Cycles of Wetting and Drying on Modulus of Rupture. Soil and Tillage Research, 11, 73-80.

Salokhe, V.M. and Gee-Clough, D. (1988)
Modes of Wet Clay Soil Behaviour under a Single Cage Wheel Lug. Journal of Terramechanics, Vol. 25, No. 4, 273-285.

Sanchez, P.A. (1973a)
Puddling Tropical Rice Soils: Effect of Water Losses. Soil Sci. 115 (2), 303-308.

Sanchez, P.A. (1973b)
Puddling Tropical Rice Soils: Growth and Nutritional Aspects. Soil Sci. 115 (2), 149-158.

Sanchez, P.A.(1976)
Soil Management in Rice Cultivation Systems. In Properties and Management of Soils in the Tropics. John Wiley and Sons, New York.

Sarker, R.I. (1985)
Effect of Tillage on Water Use. Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh, IWM-11.

Sarker, R.I., Hussain, D. and Dutta, S.C. (1985)
Determination of Plough Pan and Estimation of Water Requirements for Land Soaking and Land Preparation for Four Selected Irrigation Schemes. Dept. of Irrigation and Water management, Bangladesh Agricultural University, Mymensingh.

Scarlett, A.J. (1988)
An Investigation Into Impact Fracture of Soil Aggregates. PhD. Thesis (Unpub.), Silsoe College.

Seliq, E.T. and Nelson, R.D. (1964)
Observations of Soil Cutting with Blades. Journal of Terramechanics, Vol.1, No. 3, 32-53.

Sharma, P.K. and De Datta, S.K. (1985)
Puddling Influence on Soil Rice Development and Yield. Soil Sci. Soc. Am. J. Vol. 49, 1451-1457.

Sinha, M.P. (1964)
A Study of the Measurement of Puddling and Comparative Performance of Different Implements for Puddling in Rice Cultivation. Paper No. IRC/AE-64/17, Food and Agriculture Organization of the United Nations International Rice Commission Third Meeting, Manila, Philippines.

Siemens, J.C. (1963)
Mechanics of Soil under the Influence of Model Tillage Tools. Phd. Thesis (Unpub.), University of Illinois, Urbana, Ill.

Siemen, J.C.; Weber, J.A. and Thornburn, T.H. (1965)
Mechanics of Soil as Influenced by Model Tillage Tools. Trans. of the ASAE.Vol.8, No.1, 1-7.

Singh, J. (1961)
Note on Measurement of Puddling. Paper Presented at Agricultural Implement Seminar. ICAR, New Delhi.

Smith, D.L.O.; Godwin, R.J. and Spoor, G. (1988)
Modelling Soil Disturbance due to Tillage and Traffic. Paper presented at NATO Advanced Research Workshop on Mechanics and Related Processes in Structured Agricultural Soils, Minnesota, USA.

Soane, W. (1956)
Some Basic Considerations of Soil Mechanics as Applied to Agricultural Engineering. NIAE Translation No. 53.

Sokolovski, V.V. (1965)
Statics of Soil Media. Pergamon Press.

Spoor, G. (1969)
Design of Soil Engaging Implements. Farm Machine Design.

Spoor, G. (1975)
Shatter Matters (Subsoiling With Winged Tines). Power farming. 54 (9) 14-15.

Spoor, G. (1976)
More Shatter Matters. Power Farming. 55 (1) 34-35.

Spoor, G. and Godwin, R.J. (1978)
An Experimental Investigation into the Deep Loosening of Soil by Rigid Tines. J.agric. Engng. Res., 23 (3), 243-258.

Spoor, G. and Godwin, R.J. (1979)
Soil Deformation and Shear Strength Characteristics of Some Clay Soils at Different Moisture Contents. Journal of soil Science, 30, 483-498.

Spoor, G. and Godwin, R.J. (1979)
Effect of Tine Position on the Performance of Multitined Implements. Proc. 8th Conf. Intl. Soil and Tillage Res. Org.

Spoor, G.; Leeds-Harrison, P.B. and Godwin, R.J. (1982)
Some Fundamental Aspects of the Formation, Stability and Failure of Mole Drainage Channels. Journal of Soil Science 33, 411-425.

Spoor, G. and Fry, R.K. (1983)
Field Performance of Trenchless Drainage Tines and Implications for Drainage System Efficiency. J. agric. Engng. Res., 28, 319-335.

Spoor, G. and Fry, R.K. (1984)
Soil Disturbance Generated by Deep Working Low Rake Angle Narrow Tines. J. agric. Engng. Res., 28 (3) 217-234.

Spoor, G.; Cohran, B.J. and Chakkaphak, C. (1985a)
Implement Design for Lowland Rice Based Cropping Systems. Soil Physics and Rice. 309-322.

Spoor, G.; Miller, S.M. and Godwin, R.J. (1985b)
Mole Channel Stability. Report to Agriculture and Food Research Council. Reference No: AG 63/165, Department of Agricultural Engineering, Silsoe College, Bedford.

Stafford, J.V. (1979)
The Performance of a Rigid Tine in Relation to Soil Properties and Speed. J. agric. Engng. Res., 24, 41-56.

Stafford, J.V. (1981)
An Application of Critical State Soil Mechanics: The Performance of Rigid Tines. J. agric. Engng. Res., Vol. 26, No. 5, 387-401.

Stafford, J.V. and Tanner, D.W. (1983a)
Effect of Rate on Soil Shear Strength and Soil Metal Friction: Shear Strength. Soil Tillage Res., 3 (3), 245-260.

Stafford, J.V. and Tanner, D.W. (1983b)
Effect of Rate on Soil Shear Strength and Soil Metal Friction: Soil Metal Friction. Soil Tillage Res. 3 (4) 321-330.

Stafford, J.V. (1984)
Force Prediction Models for Brittle and Flow Failure of Soil by Draught Tillage Tools. J. agric. Engng. Res., 29 (1), 51-60.

Staple, W.J. and Gupta, R.P. (1966)
Infiltration into Homogeneous and Layered Columns of Aggregated Loam, Silt Loam and Clay Soil. Can. J. Soil Sci. 46 : 293-305.

Steel, R.G.D. and Torrie, J.H. (1960)
Principles and Procedures of Statistics. Mc Graw Hill Book Company, Inc. New York.

Stengel, P.(1988)
Cracks Formation During Swelling:Effects on Soil Structure Regeneration After Compaction. Proc. Int. Soil Tillage Research. 11th Int. Conference, Edinburg, Scotland, 147-152.

Stirk, G.B. (1954)
Some Aspects of Soil Shrinkage and the Effect of Cracking upon Water Entry into the Soil. Aust. J. Agric. Res. 5, 279-290.

Stout, B.A. (1966)
Equipment for Rice Production. FAO agric. Dev. Paper 84, 169.

Subbaiah S.V.,Singh, R.P., Pillai, K.G., Dhandapani, K.R. (1984)
Effect of Water Management Practices on Penetration. Resistance of Paddy soil. Agricultural Mechanization in Asia, Africa and Latin America, Volume 15 (4) 35-37.

Swick, W.C. and Perumpral, J.V. (1985)
A Model for Predicting Dynamic Soil Tool Interaction. Proc. Int. Conf. Soil Dynamics. Auburn University, Auburn, Alabama. 384-399.

Taneja, M.L. and Patnaik, S. (1962)
Technique and Determining the Degree and Depth of Soil Puddle. Rice Newsletter, 10 (1), 27-28.

Tanner, D.W. (1960)
Furtherwork on the Relationship Between Rake Angle and the Performance of Simple Cultivation Implements. J. agric. Engng. Res., 5 (3) 307-315.

Terzaghi, K.(1942)
Theoretical Soil Mechanics. Wiley, New York.

Throne, D.W. and Peterson, H.B. (1950)
Irrigated Soils: Their Fertility and Management. Blakistan Co., Philidelphia.

Tiwari, G. and Singh, B. (1985)
Effect of Blade Angle and Width of Tractor Operated Rotary Puddler on Puddling Quality. J. agric. Engng. ISAE, Vol. 22 (2) 1-8.

Towner, G.D. (1973)
An Examination of the Fall Cone Method for the Determination of Some Strength Properties of Remoulded Agricultural Soils. Journal of Soil Science, Vol.24, No.4, 470-479.

Towner, G.D. (1987a)
The Mechanics of Cracking of Drying Clay. J. agric. Engng. Res., 36, 115-124.

Towner, G.D. (1987b)
The Tensile Stress Generated in Clay Through Drying. J. agric. Engng. Res., 37, 279-289.

UMAS. (1982)
Report on Farmers Mechanisation Centre. Universiti Pertanian Malaysia, Serdang, Selangor. Malaysia.

U.N. (1970)
The Mechanisation of Rice Cultivation. Economic Conmmission for Europe. AGRI/MECH/44.

Ura, T. and Tamamoto, Y. (1978)
Stability of Dragged Anchors Institute of Industrial Science, University of Tokyo, Japan. 27 (4), Serial No 174, 1-19.

Utomo, W.H. and Dexter, A.R. (1981)
Soil Friability. J. Soil Science. 32, 203-213.

Valera, A. (1977)
Field Studies on Water Use and Duration for Land Preparation for Lowland Rice. M.S. Thesis (Unpub.), UPLB, Los Banos, Laguna.

Vamadevan, V.K. and Dastane, N.G. (1968)
Suitability of Soils for Irrigated Rice. Riso, 17, 243-250.

Van Bavel, C.H.M. (1952)
Compact Wet Sieving Apparatus for Soil Aggregate Analysis. Agron. J. 44, 97-98.

Van de Goor, G.A.W. (1950)
Research on Rice Irrigation. Contr. Gen. Agr. Res. Sta. Bogor (Indonesia), No. 112, 34 pages.

van Dijk, A.D. (1971)
Tillage Practices and Tillage Equipment as used for Rice Production on Large Estates in Surinam. FAO Meeting of Experts on the Mechanisation of Rice Production and Processing, Paramaribo, Surinam.

Waldron, L.J. and Manbeian, T. (1969)
Soil Moisture Characteristics by Osmosis with Polythelene Glycol. A Simple System with Osmotic Pressure Data and Some Results. Soil Science. Vol. 110, No. 6 401-404.

Wickham, T. (1972)
Water Management in the Humid Tropics-A Farm Level Analysis. PhD. Dissertation, Cornell University, Ithaca, New York.

Willatt, S.T. and willis, A.H. (1965)
A Study of the Trough Formed by the Passage of Tines Through the Soil. J. agric. Engng. Res., 10 (1), 1-14.

Wismer, R.D. and Luth, H.J. (1972)
Performance of Plane Soil Cutting Blades in Clay. Trans. of the ASAE 15 (2), 211-216.

Witney, B.D. (1968)
The Determination of Soil Particle Movement in Two Dimensional Failure. Journal of Terramechanics 5 (1), 39-52.

Wong, J.Y. and Reece, A.R. (1966)
Soil Failure Beneath Rigid Wheels. Proc. 2nd Int. Conf. of the International Society of Terrain-Vehicle Systems, Quebec.

Yadav, J.S.P. (1972)
Water Management and Irrigation Scheduling in Relation to Rice Production. Oryza 9 (2) 77-96.

Yoder, R.E. (1936)
A Direct Method of Aggregate Analysis of Soils and a Study of the Physical Nature of Erosion Losses. J. Am. Soc. Agron. 28, 337-351.

Yong, R.N. and Warkentin, B.P. (1975)
Soil Properties and Behaviour. Elsevier, Amsterdam.

Youker, R.E. and Mc. Guinness, J.L. (1957)
A Short Method of Obtaining Mean Weight Diameter Value of Aggregate Analysis of Soil. Soil Science, 83: 291-294.

Youngs, E.G. (1981)
Use of Similar Media Theory in Infiltration and Runoff Relationships. In Pre-symposium Proceedings of the International

Symposium on Rainfall-Runoff Modelling, Mississippi State University, Mississippi State, MS 109-110.

Zelenin, A.N. (1950)
Basic Physics of the Theory of Soil Cutting. (NIAE Translation, not numbered).

Zhang, T.L. and Shao, Y.J. (1984)
The Analysis of the Dynamic Performance of a Single Lug. Proc. 8 th Int. Conf. ISTVS, Cambridge, UK. 575-591.

Table 2.1 Effect of method of wetting on the percentage of aggregates stable in water (Kemper and Koch, 1966).

Soils	Wetting technique		
	by immersion	under suction	under vacuum
Soils of western USA	41	74	70
Soils of southeastern USA	83	98	99

Table 2.2 Water use for land preparation in various Asian countries (After Kung and Atthayodhin, 1968).

Country	Days of preparation	Depth of water mm	Soil
China	-	200-400	Heavy
Japan	-	120	Light
Korea	-	122	-
Taiwan	-	180	-
India	15	298	-
Bangladesh	5-10	180	-
Thailand	-	300-400	-
Malaysia	-	180	-
Philippine	30	220-290	Clay

Table 2.3 Average labour and power requirements in secondary tillage for producing rice (Adapted from Johnson, 1973).

Source of Power	Manual (h /ha)	Animal (h /ha)	Engine (hp-h /ha)
(a) Hand hoe and rake.	100-250	-	-
(b) Comb harrow drawn by 4-5 men.	250-500	-	-
(c) Buffalo and comb harrow multiple passes.	64-100	64-100	-
(d) Animal drawn wetland puddler, rotary type.	8-33	16-66	-
(e) Power tiller			
(i) Traction type, 4-6 hp with puddling wheels and comb harrow.	16-24	-	80-150
(ii) Rotary tiller, 5-10 hp.	10-20	-	100-160
(f) Rotary tiller and 35-60 hp tractor with cagewheels on wet soil.	4-32	-	140-300

Table 3.1 A summary of the experimental treatments and the assess ments made in wetland soil-implement mechanics study.

Experimental Treatments	Assessments
1. Clod wetting. (3 clod sizes and 3 initial moisture contents). a) unconfined and b) confined states	1. Moisture profile. 2. Volume change (Blake, 1965). 3. Dry bulk density. 4. Clod strength (Hansbo, 1957). 5. Verification of infiltration models.
2. Clod drying. (3 clod sizes and 1 moisture content).	1. Moisture profile. 2. Volume change (Blake, 1965). 3. Dry bulk density.
3. Single tine experiments. (1 speed, 3 rake angles, 3 depths, 2 widths and 3 moisture contents Further experiments at 70% moisture content (1 speed, 3 rake angles, 2 depths and 4 widths).	1. Draught force. 2. Vertical force. 3. Magnitude and direction of resultant force. 4. Profile of disturbance. 5. Extent of lateral heave. 6. Disturbance pattern a) Soil particle trajectory (Spoor and Fry,1983). b) Glass sided tank study. 7. Soil physical and mechanical properties. 8. Development and verification of soil failure models based on lateral failure theory and Hettiaratchi and Reece two dimensional failure (1974) for forward and vertical inclined tines. 9. Development and verification of static wedge theory for the draught and vertical force of the backward raked tine
4. Multiple tines experiments. (3 spacings, 2 depths, 2 moisture contents, 1 speed and 90^0 rake angle)	1. Draught force. 2. Vertical force. 3. Profile of disturbance.
5. Soil puddling. (4 water-soil ratios, 1 speed and 1 puddler)	1. Wet bulk density. 2. Percentage aggregate size dis tribution (van Bavel, 1952)

Table 3.2 Detailed treatments of each experiment conducted.

Experiments	Detailed Treatments
1. Clod wetting	clod sizes: 25, 45 and 65 mm cubes initial moisture contents: 13%, 22% and 38% (dry basis)
2. Clod drying	clod sizes: 25, 45 and 65 mm cubes initial moisture content: 38% (dry basis)
3. Single tine	moisture contents: 42% and 56% (dry basis) speed: 0.1 m/s rake angles: 45^0, 90^0 and 135^0 depths: 50.8, 101.6 and 152.4 mm tine widths: 25.4, 50.8 mm moisture content: 70% (dry basis) speed: 0.1 m/s rake angles: 45^0, 90^0 and 135^0 depths: 50.8 mm (all widths), 101.6 mm (all widths) and at 152.4 mm(25.4 mm and 50.8 mm tines only)
4. Multiple tines	moisture contents: 56% and 70% (dry basis) tine spacings: 101.6 mm, 152.4 mm and 203.2 mm speed: 0.1 m/s depth of leading tines: 50.8 and 101.6 mm depth of trailing tine: 101.6 mm tine rake angle: 90^0
5. Soil puddling	water-soil ratios: 0.8, 1.0, 1.2 and 1.4 1 puddler rotational speed: 2000 rev/min power input: 30 watts stirring time: 5, 10 and 20 seconds

Table 5.1a Physical properties of experimental soil.

Sand	Silt	Clay	L.P.L	U.P.L	P.Index
2.52%	32.68%	64.80%	24%	90%	66%

Table 5.1b Mechanical properties of experimental soil.

moisture content(%)	c (kN/m^2)	c_a (kN/m^2)	ϕ $(^0)$	δ $(^0)$	γ (kg/m^3)
42	29	0.20	1	18	1250
56	16	0.90	0	22	1000
70	6	1.14	0	20	940

c = soil shear strength

c_a = soil-metal shearing resistance

ϕ = angle of soil shear strength

δ = angle of soil-metal shearing resistance

γ = soil dry bulk density

Table 5.2 A summary of results on the effect of clod size, confining state and wetting period on clod volume for different initial moisture contents. Units are in (cm^3).

Size	Wetting period (days)	Initial moisture contents (%)					
		13		22		38	
		C	U	C	U	C	U
Small	0	9.89	12.49	10.31	14.07	14.12	18.33
	1	14.08	14.63	13.13	15.04	13.57	18.21
	3	14.58	16.58	13.32	15.36	13.90	18.04
	5	14.04	17.19	13.32	15.60	14.15	18.69
	7	14.71	17.16	13.45	15.62	14.01	18.24
Medium	0	58.58	72.90	66.91	78.59	82.66	85.35
	1	77.74	78.39	75.27	82.32	81.21	86.54
	3	80.90	88.83	80.08	86.18	81.33	87.73
	5	79.68	96.54	81.32	83.82	81.41	87.69
	7	82.57	102.31	81.24	88.11	81.60	85.86
Large	0	199.87	207.47	221.69	230.14	275.22	291.38
	1	237.64	233.14	228.38	242.33	274.19	285.05
	3	273.74	270.58	242.53	246.18	278.68	295.73
	5	278.05	273.48	257.23	251.04	280.02	290.73
	7	279.40	282.37	281.20	259.42	281.02	288.91
LSD (0.05)		7.06		6.12		4.86	

C = confined case, U = unconfined case.

LSD = Least significant difference.

Table 5.3 A summary of results on the effect of clod size, confining state and wetting period on clod dry bulk density for different initial moisture contents. Units are in (Mg/m^3).

Size	Wetting period (days)	Initial moisture contents (%)					
		13		22		38	
		C	U	C	U	C	U
Small	0	1.81	1.93	1.69	1.61	1.29	1.29
	1	1.28	1.63	1.38	1.57	1.30	1.30
	3	1.26	1.46	1.37	1.58	1.32	1.32
	5	1.27	1.41	1.35	1.47	1.30	1.28
	7	1.29	1.36	1.32	1.45	1.30	1.30
Medium	0	1.83	1.92	1.60	1.54	1.29	1.29
	1	1.36	1.73	1.41	1.50	1.32	1.28
	3	1.30	1.52	1.32	1.49	1.32	1.27
	5	1.33	1.47	1.32	1.46	1.31	1.28
	7	1.29	1.37	1.31	1.42	1.32	1.28
Large	0	1.79	1.93	1.62	1.66	1.29	1.29
	1	1.52	1.62	1.58	1.56	1.29	1.27
	3	1.32	1.39	1.48	1.53	1.28	1.28
	5	1.30	1.39	1.40	1.48	1.27	1.28
	7	1.29	1.38	1.27	1.47	1.29	1.28
LSD (0.05)		0.09		0.08		0.04	

C = confined case, U = unconfined case.

LSD = Least significant difference.

Table 5.4 A summary of results on the effect of clod size, confining state and wetting period on the rate of water uptake by 0-10 mm layer for different initial moisture contents.

Size	Wetting period (days)	Initial moisture contents (%)					
		13		22		38	
		C	U	C	U	C	U
Small	0	10.09	12.46	20.09	20.79	37.28	38.24
	1	37.14	31.95	33.71	27.02	38.18	39.26
	3	40.04	31.49	38.30	27.19	38.29	41.91
	5	39.22	32.96	39.76	30.88	38.83	42.26
	7	39.19	32.75	40.97	32.02	39.58	42.77
Medium	0	10.47	12.43	19.08	19.44	37.90	38.77
	1	36.87	30.73	32.14	26.98	38.34	41.52
	3	38.99	30.60	36.62	27.75	38.81	41.68
	5	38.33	32.88	39.21	30.11	38.31	43.05
	7	41.52	35.36	40.05	32.56	38.64	42.79
Large	0	10.02	9.40	18.22	18.03	37.48	39.06
	1	32.26	28.60	28.84	26.92	40.13	40.53
	3	38.63	35.67	34.99	33.46	39.45	41.64
	5	41.90	38.80	36.38	35.24	40.58	42.63
	7	40.30	38.24	40.04	41.02	40.49	43.71
LSD (0.05)		1.78		4.96		0.98	

C = confined case, U = unconfined case.

LSD = Least significant difference.

Table 5.5 A summary of results on the effect of clod size and wetting period on depth of cone penetration for two initial moisture contents.

a) Initial moisture content at = 21.3 % dry basis.

Clod size	Wetting period (days)							
	0	1	2	3	4	5	6	7
Small	0.6	2.5	2.6	2.7	2.7	2.8	2.8	2.8
Medium	0.8	2.6	2.6	2.6	2.7	2.7	2.7	2.6
Large	0.7	2.1	2.3	2.3	2.4	2.5	2.6	2.6

Least significant difference = 0.29

b) Initial moisture content = 37.6 % dry basis

Clod size	Wetting period (days)							
	0	1	2	3	4	5	6	7
Small	2.7	2.7	2.8	2.8	2.7	3.0	3.0	3.0
Medium	2.7	2.8	2.8	2.9	2.8	2.9	2.9	2.8
Large	2.7	2.7	2.7	2.8	2.7	2.8	2.8	2.8

Not significant at 95% confidence level.

Table 5.6 Predicted and experimental saturation values for 60 mm cube. Units are in percentage.

	Soil layer, mm (from wetted end)					
	0-10	10-20	20-30	30-40	40-50	50-60
initial state	76.26	86.09	88.50	90.03	90.56	87.07
Day 1						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	104.35	90.86	86.75	85.13	84.56	81.53
Day 2						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	109.50	94.52	86.44	83.66	81.64	78.09
Day 3						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	116.21	100.50	88.69	79.78	77.02	76.82
Day 4						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	114.07	109.65	99.63	82.36	78.55	79.21
Day 5						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	103.47	95.66	90.96	89.16	88.61	86.69
Day 6						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	106.80	104.16	103.97	89.98	83.85	80.68
Day 7						
calculated	100.52	96.54	92.54	88.50	84.53	80.35
experimental	101.51	97.63	97.21	93.03	94.04	90.60

Table 5.7 Predicted and experimental height of infiltration(mm).

a) small cube

Number of days	Experimental value	Predicted value
Day 1	4.74	1.80
Day 2	6.47	2.55
Day 3	7.52	3.12
Day 4	8.74	3.60
Day 5	9.80	4.02
Day 6	11.79	4.41
Day 7	12.50	4.76

b) Medium cube

Day 1	3.86	1.80
Day 2	4.86	2.55
Day 3	5.64	3.12
Day 4	7.73	3.60
Day 5	9.22	4.02
Day 6	9.28	4.41
Day 7	9.64	4.76

c) Large cube

Day 1	1.96	1.80
Day 2	4.11	2.55
Day 3	5.45	3.12
Day 4	5.66	3.60
Day 5	5.95	4.02
Day 6	5.99	4.41
Day 7	5.99	4.76

Table 5.8 A summary of the average side disturbance from tine side for three moisture contents (dry basis). Units are in mm.

Depth (mm)	Rake angle (degrees)	Moisture contents(%)					
		42		56		70	
		25.4	50.8	25.4	50.8	25.4	50.8
50.8	45	32.60	34.60	35.60	44.60	37.30	52.30
	90	33.97	41.27	42.30	47.90	50.60	54.60
	135	40.63	46.30	52.30	59.60	57.30	66.30
101.6	45	38.90	46.30	48.90	61.30	50.60	67.90
	90	42.30	49.60	52.30	64.60	63.90	77.90
	135	52.30	61.27	68.90	84.60	75.70	93.60
152.4	45	40.30	50.30	50.60	64.60	60.60	77.30
	90	47.30	54.60	55.30	69.60	69.60	91.30
	135	61.60	79.40	81.10	109.60	88.90	121.30
LSD		4.08		6.72		6.82	

LSD = Least significant difference

Table 5.9 A summary of the average side disturbance (mm) from tine side for three depths and four tine widths at 70% moisture content.

Depth (mm)	Rake angle (degrees)	Width of tine (mm)			
		25.4	50.8	101.6	152.4
50.8	45	37.30	52.30	25.90	23.80
	90	50.60	54.60	30.90	32.10
	135	57.30	66.30	67.50	72.10
101.6	45	50.60	67.90	35.90	35.50
	90	63.90	77.90	50.90	40.50
	135	75.60	93.60	85.90	90.50

Least significant difference = 4.80

Table 5.10 A summary of mean draught force (N) over three blocks for three depths at 42% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Width of tine (mm) 25.4	50.8
50.8	45	142.25	214.50
	90	214.50	286.34
	135	316.10	512.14
101.6	45	327.79	480.50
	90	376.05	679.98
	135	637.81	1144.25
152.4	45	500.36	772.15
	90	555.09	879.96
	135	1303.11	1913.04

Least significant difference = 69.67 N

Table 5.11 A summary of mean draught force (N) over three blocks for three depths at 56% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Width of tine (mm) 25.4	50.8
50.8	45	78.48	118.35
	90	94.12	183.56
	135	174.40	282.56
101.6	45	180.85	258.52
	90	212.55	352.40
	135	351.89	565.12
152.4	45	278.77	408.30
	90	306.87	454.84
	135	753.70	1145.82

Least significant difference = 45.62 N

Table 5.12 A summary of mean draught force (N) over three blocks for three depths at 70% moisture content (dry basis)

Depth (mm)	Rake angle (degrees)	Width of tines(mm)	
		25.4	50.8
50.8	45	29.43	44.38
	90	40.22	64.46
	135	65.40	105.96
101.6	45	67.82	101.47
	90	81.75	138.95
	135	164.66	252.07
152.4	45	118.24	150.94
	90	123.64	220.88
	135	298.42	429.20

Least significant difference = 20.93 N

Table 5.13 A summary of mean draught force (N) over three blocks for two depths at 70% moisture content (dry basis)

Depth (mm)	Rake angle (degrees)	Width of tines(mm)			
		25.4	50.8	101.	152.4
50.8	45	29.43	44.38	62.34	85.89
	90	40.22	64.46	126.41	189.71
	135	65.40	105.96	222.42	292.12
101.6	45	67.82	101.47	142.39	191.93
	90	81.75	138.95	188.50	395.16
	135	164.66	252.07	403.64	577.80

Least significant difference = 16.11 N

Table 5.14 A summary of mean vertical force (N) over three blocks for three depths at 42% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Width of tine (mm) 25.4	50.8
50.8	45	-51.58	-151.55
	90	45.03	130.03
	135	208.44	416.88
101.6	45	-88.27	-202.76
	90	54.22	146.99
	135	398.75	797.50
152.4	45	-107.46	-326.26
	90	63.25	158.30
	135	606.10	1212.20

- indicates downward direction

Least significant difference = 39.79 N

Table 5.15 A summary of mean vertical force (N) over three blocks for three depths at 56% moisture content (dry basis)

Depth (mm)	Rake angle (degrees)	Width of tine (mm) 25.4	50.8
50.8	45	-27.78	-68.40
	90	29.80	53.16
	135	115.00	236.00
101.6	45	-45.93	-119.75
	90	32.39	65.46
	135	229.99	465.00
152.4	45	-47.93	-183.61
	90	36.27	87.46
	135	346.15	692.28

- indicates downward direction

Least significant difference = 16.57 N

Table 5.16 A summary of mean vertical force (N) over three blocks for three depths at 70% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Width of tine(mm)	
		25.4	50.8
50.8	45	-15.53	-32.40
	90	9.81	14.95
	135	43.13	90.00
101.6	45	-30.66	-53.82
	90	17.77	33.28
	135	86.25	172.50
152.4	45	-62.08	-121.93
	90	18.54	56.16
	135	135.44	258.75

- indicates downward direction

Least significant difference = 17.36 N

Table 5.17 A summary of mean vertical force (N) over three blocks for two depths at 70% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Width of tine(mm)			
		25.4	50.8	101.6	152.4
50.8	45	-15.53	-32.40	-55.54	-66.40
	90	9.81	14.95	50.32	67.59
	135	43.13	90.00	180.00	270.00
101.6	45	-30.66	-53.82	-100.58	-135.30
	90	17.77	33.28	63.38	102.70
	135	86.25	172.50	345.00	517.50

- indicates downward direction

Least significant difference = 14.45 N

Table 5.18 Magnitude and direction of the resultant force.

Treatment	Moisture content (% dry basis)					
	42		56		70	
wxzxrake angle	R (N)	0_R^{0}	R(N)	0_R^{0}	R (N)	0_R^{0}
25.4x50.8x45^0	151.31	19.93*	83.25	19.49*	33.28	27.82*
25.4x50.8x90^0	219.18	11.86	98.72	17.57	41.39	13.70
25.4x50.8x135^0	378.65	33.40	208.90	33.40	78.29	33.40
25.4x101.6x45^0	339.47	15.07*	186.59	14.25*	74.43	24.33*
25.4x101.6x90^0	379.94	8.20	215.00	8.66	83.66	12.26
25.4x101.6x135^0	752.20	32.01	420.39	33.17	185.88	27.65
25.4x152.4x45^0	511.77	12.12*	282.86	9.76*	133.55	27.70*
25.4x152.4x90^0	558.68	6.50	309.01	6.74	127.00	8.39
25.4x152.4x135^0	1437.17	24.94	829.39	24.67	327.72	24.41
50.8x50.8x45^0	262.61	35.24*	146.53	36.13*	54.95	36.13*
50.8x50.8x90^0	314.48	24.42	191.10	16.15	66.17	13.06
50.8x50.8x135^0	660.36	39.15	368.15	39.87	139.02	40.34
50.8x101.6x45^0	521.53	22.88*	284.91	24.85*	114.86	27.94*
50.8x101.6x90^0	695.69	12.20	358.44	10.36	142.88	13.47
50.8x101.6x135^0	1394.75	34.88	640.87	39.45	305.44	34.39
50.8x152.4x45^0	838.25	22.91*	447.68	24.21*	194.04	38.93*
50.8x152.4x90^0	894.09	10.20	463.17	10.88	227.91	14.27
50.8x152.4x135^0	2264.76	32.36	1338.71	31.14	501.16	31.08
101.6x50.8x45^0	-	-	-	-	83.49	41.69*
101.6x50.8x90^0	-	-	-	-	93.00	21.70
101.6x50.8x135^0	-	-	-	-	286.14	38.98
101.6x101.6x45^0	-	-	-	-	174.32	35.24*
101.6x101.6x90^0	-	-	-	-	198.87	17.68
101.6x101.6x135^0	-	-	-	-	530.99	40.52
152.4x50.8x45^0	-	-	-	-	108.56	37.71*
152.4x50.8x90^0	-	-	-	-	116.48	19.61
152.4x50.8x135^0	-	-	-	-	397.79	42.75
152.4x101.6x45^0	-	-	-	-	234.83	35.18*
152.4x101.6x90^0	-	-	-	-	268.23	17.96
152.4x101.6x135^0	-	-	-	-	775.67	41.84

w = tine width (mm)
z = operating depth (mm)
R = the resultant force (Newton)
0_R = direction of the resultant force to the horizontal (degree)
* = acting downwards

Table 5.19 Experimental results compared with total force of tines when operated independently.

a) Draught force at 56% moisture content

Treatment	experimental (N)	calculated (total of independent operations) (N)
3 TA	349.82	400.79
3 TB	631.91	637.65
3 TC	368.98	400.79
3 TD	642.27	637.65
3 TE	396.23	400.79
3 TF	661.10	637.65

b) Draught force at 70% moisture content

Treatment	experimental (N)	calculated (total of independent operations) (N)
3 TA	137.24	162.19
3 TB	226.32	245.25
3 TC	146.67	162.19
3 TD	230.04	245.25
3 TE	153.92	162.19
3 TF	235.43	245.25

c) Vertical force at 56% moisture content

Treatment	experimental (N)	calculated (total of independent operations) (N)
3 TA	64.67	91.99
3 TB	71.91	97.17
3 TC	76.75	91.99
3 TD	76.30	97.17
3 TE	79.99	91.99
3 TF	80.50	97.17

d) Vertical force at 70% moisture content

Treatment	experimental (N)	calculated (total of independent operations) (N)
3 TA	45.54	48.83
3 TB	67.39	53.31
3 TC	50.07	48.83
3 TD	76.27	53.31
3 TE	57.93	48.83
3 TF	76.26	53.31

Table 5.20 Multitine spacings and working depth for two moisture contents.

Treatment	Shallow leading tines spacing(mm)	Shallow leading tines depth(mm)	Rear tine depth(mm)
3 TA	101.6	50.8	101.6
3 TB	101.6	101.6	101.6
3 TC	152.4	50.8	101.6
3 TD	152.4	101.6	101.6
3 TE	203.2	50.8	101.6
3 TF	203.2	101.6	101.6

Table 5.21 A summary of multitine results at 56% moisture content (dry basis) compared with a single tine at the same depth as the rear tine. Units are in Newtons.

Treatment	Mean Draught	Mean Vertical Force
1T	212.55	32.39
3TA	349.82	64.67
3TB	631.91	71.91
3TC	368.98	76.75
3TD	642.27	76.30
3TE	396.23	79.99
3TF	661.10	80.56
LSD (0.05)	51.00	14.33

LSD = Least significant difference.

Table 5.22 A summary of multitine results at 70% moisture content (dry basis) compared with a single tine at the same depth as the rear tine. Units are in Newtons.

Treatment	Mean Draught	Mean Vertical Force
1T	81.75	17.97
3TA	137.24	45.54
3TB	226.32	67.39
3TC	146.67	50.07
3TD	230.04	76.27
3TE	153.92	79.99
3TF	222.10	76.22
LSD (0.05)	33.57	12.09

LSD = Least significant difference.

Table 5.23 Percentage aggregate size (< 0.5 mm diameter)*

Stirring time (seconds)	Water-soil ratio			
	0.8	1.0	1.2	1.4
0	24.53 (2.91)	25.18 (3.09)	24.67 (3.00)	25.60 (0.89)
5	40.26 (2.99)	53.34 (2.86)	62.23 (7.10)	51.23 (1.22)
10	49.10 (1.19)	57.54 (3.69)	59.09 (1.38)	57.15 (3.89)
20	52.24 (1.10)	66.45 (1.06)	62.29 (1.36)	66.17 (2.51)

* mean of three replicates. Least significant difference= 4.94
Figures in brackets are standard deviation values.

Table 5.24 Wet bulk density values (Mg/m^3)*

Stirring time (seconds)	Water-soil ratio			
	0.8	1.0	1.2	1.4
5	1.49 (0.02)	1.42 (0.02)	1.27 (0.01)	1.29 (0.01)
10	1.48 (0.01)	1.35 (0.01)	1.24 (0.01)	1.26 (0.02)
20	1.48 (0.01)	1.35 (0.01)	1.23 (0.01)	1.23 (0.03)

* mean of three replicates. Least significant difference= 0.02
Figures in brackets are standard deviation values.

Table 5.25 Initial water level and level of puddled soil after stirring at different times. Units are in millimeters.

Stirring time (seconds)		Water-soil ratio							
		0.8		1.0		1.2		1.4	
		Mean*	sd	Mean*	sd	Mean*	sd	Mean*	sd
5	Hwater	44.3	0.58	59.7	0.58	66.0	1.00	73.3	0.58
	Hpuddle	42.3	0.59	46.3	1.53	52.7	0.57	52.0	0.20
10	Hwater	45.0	1.00	59.7	1.50	66.0	0.30	73.3	0.60
	Hpuddle	44.0	1.00	54.7	1.52	57.7	0.30	60.0	1.00
20	Hwater	45.0	1.00	59.7	0.59	66.0	1.00	72.7	0.60
	Hpuddle	44.0	1.00	54.7	0.60	61.0	1.00	66.7	0.73

* means of three replicates. Base area of beaker = 11.33 cm^2
Hwater = height of water level.
Hpuddle = height of puddled soil.
sd = standard deviation.

Table 6.1 Parameters used in force prediction model.

(a) Dimensionless numbers

Parameter	Rake angle (degrees)		
	45	90	135
Nca	0.80	2.00	-
N_γ	0.70	0.50	-
Nq'	1.00	1.00	1.00
Nc'	5.14	5.14	5.14
m	2.00	1.50	-

(b) Mechanical properties of experimental soil at different moisture contents.

moisture content(%)	c (kN/m^2)	c_a (kN/m^2)	ϕ (^{0})	δ (^{0})	γ (kg/m^3)
42	29	0.20	1	18	1250
56	16	0.90	0	22	1000
70	6	1.14	0	20	940

c = soil shear strength

c_a = soil-metal shearing resistance

ϕ = angle of soil shear strength

δ = angle of soil-metal shearing resistance

γ = soil dry bulk density

Table 6.2 Comparison between tine aspect ratio and the critical aspect ratio at 42% moisture content (dry basis).

Treatment w x z x α	Tine aspect ratio	Critical aspect ratio
25.4x50.8x45	2.00	2.23
50.8x50.8x45	1.00	2.17
25.4x101.6x45	4.00	2.23
50.8x101.6x45	2.00	2.17
25.4x152.4x45	6.00	2.23
50.8x152.4x45	3.00	2.17
25.4x50.8x90	2.00	0.96
50.8x50.8x90	1.00	0.96
25.4x101.6x90	4.00	0.96
50.8x101.6x90	2.00	0.96
25.4x152.4x90	6.00	0.96
50.8x152.4x90	3.00	0.96
25.4x50.8x135	-	-
50.8x50.8x135	-	-
25.4x101.6x135	-	-
50.8x101.6x135	-	-
25.4x152.4x135	-	-
50.8x152.4x135	-	-

Table 6.3 Comparison between tine aspect ratio and the critical aspect ratio at 56% moisture content (dry basis).

Treatment w x z x α	Tine aspect ratio	Critical aspect ratio
25.4x50.8x45	2.00	2.18
50.8x50.8x45	1.00	2.09
25.4x101.6x45	4.00	2.18
50.8x101.6x45	2.00	2.09
25.4x152.4x45	6.00	2.18
50.8x152.4x45	3.00	2.09
25.4x50.8x90	2.00	0.96
50.8x50.8x90	1.00	0.95
25.4x101.6x90	4.00	0.96
50.8x101.6x90	2.00	0.95
25.4x152.4x90	6.00	0.96
50.8x152.4x90	3.00	0.95
25.4x50.8x135	-	-
50.8x50.8x135	-	-
25.4x101.6x135	-	-
50.8x101.6x135	-	-
25.4x152.4x135	-	-
50.8x152.4x135	-	-

Table 6.4 Comparison between tine aspect ratio and the critical aspect ratio at 70% moisture content (dry basis)

Treatment w x z x α	Tine aspect ratio	Critical aspect ratio
25.4x50.8x45	2.00	2.01
50.8x50.8x45	1.00	1.86
101.6x50.8x45	0.50	1.65
152.4x50.8x45	0.33	1.50
25.4x101.6x45	4.00	2.01
50.8x101.6x45	2.00	1.86
101.6x101.6x45	1.00	1.65
152.4x101.6x45	0.67	1.50
25.4x152.4x45	6.00	2.01
50.8x152.4x45	3.00	1.86
25.4x50.8x90	2.00	0.95
50.8x50.8x90	1.00	0.94
101.6x50.8x90	0.50	0.92
152.4x50.8x90	0.33	0.90
25.4x101.6x90	4.00	0.95
50.8x101.6x90	2.00	0.94
101.6x101.6x90	1.00	0.92
152.4x101.6x90	0.67	0.90
25.4x152.4x90	6.00	0.95
50.8x152.4x90	3.00	0.94
25.4x50.8x135	-	-
50.8x50.8x135	-	-
101.6x50.8x135	-	-
152.4x50.8x135	-	-
25.4x101.6x135	-	-
50.8x101.6x135	-	-
101.6x101.6x135	-	-
152.4x101.6x135	-	-
25.4x152.4x135	-	-
50.8x152.4x135	-	-

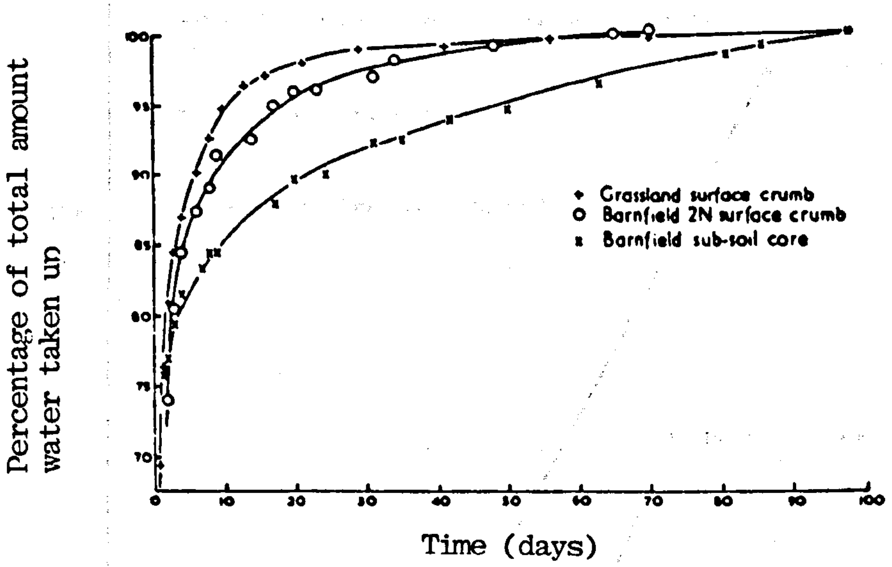


Figure 2.1 Rate of water uptake with time of crumbs dried to wilting point (Emerson, 1955).

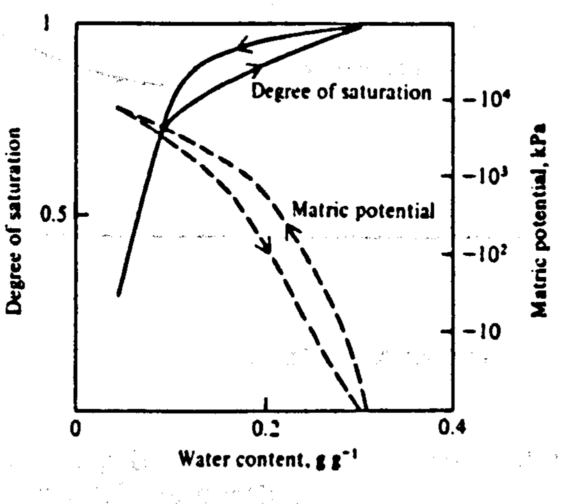


Figure 2.2 The degree of saturation of remoulded clay blocks which change their volume during wetting and drying. The change of matric potential with water content is also shown (Holmes, 1955).

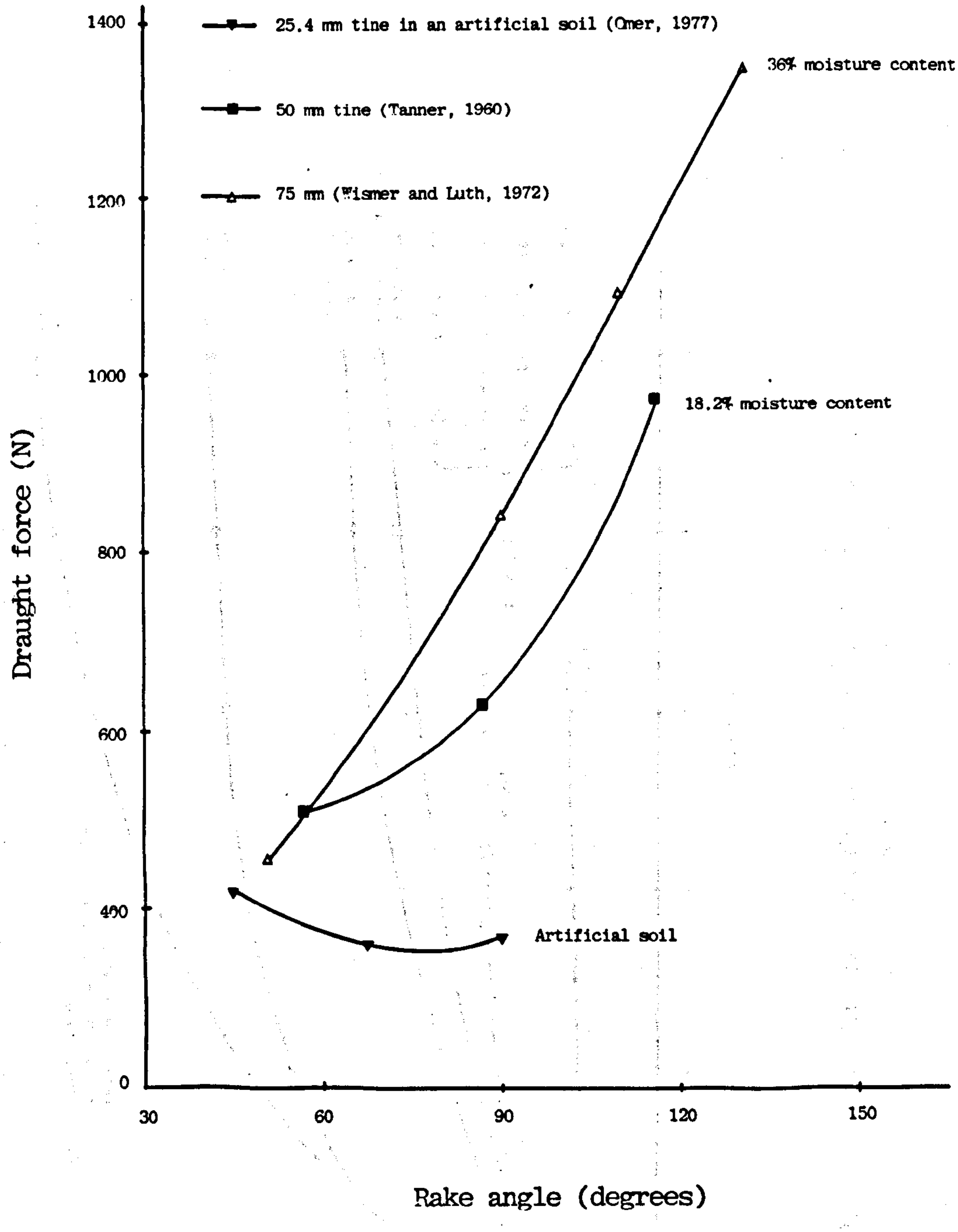


Figure 2.3 Relationship between draught force and tine rake angle. Data for 50.8 mm depth .

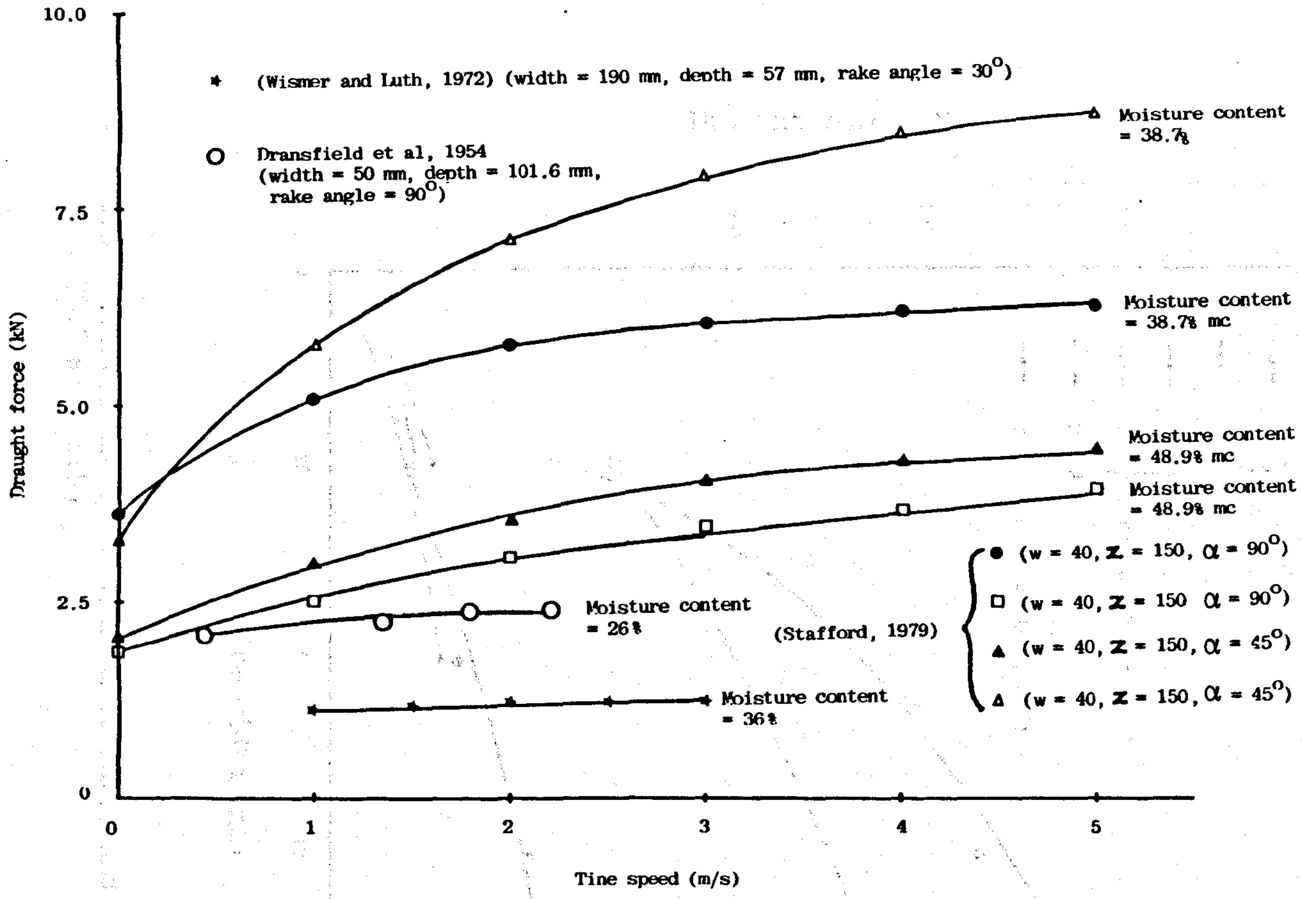


Figure 2.4 Relationship between draught force and tine speed.

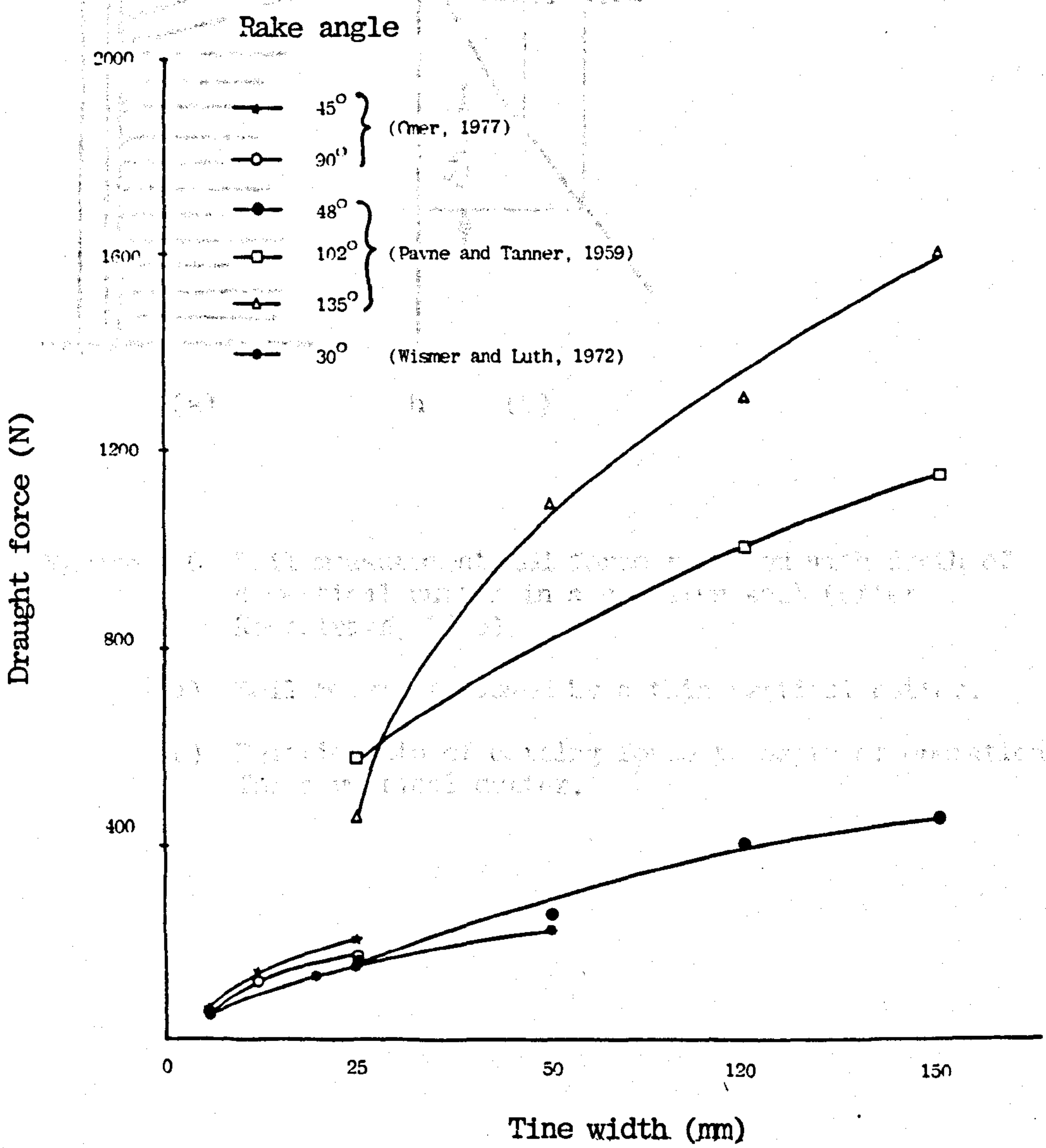


Figure 2.5 Relationship between draught force and tine width (data for 50.8 mm depth)

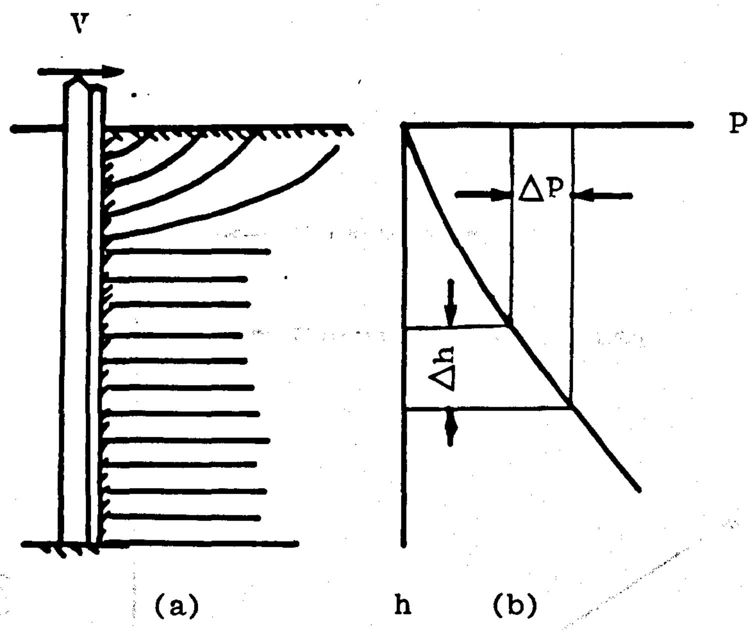


Figure 2.6 Soil measurement and force relation with depth of a vertical cutter in a cohesive soil (after Kostritsyn, 1956)

a) Soil movement caused by a thin vertical cutter.

b) Relationship of cutting force to depth of operation for a vertical cutter.

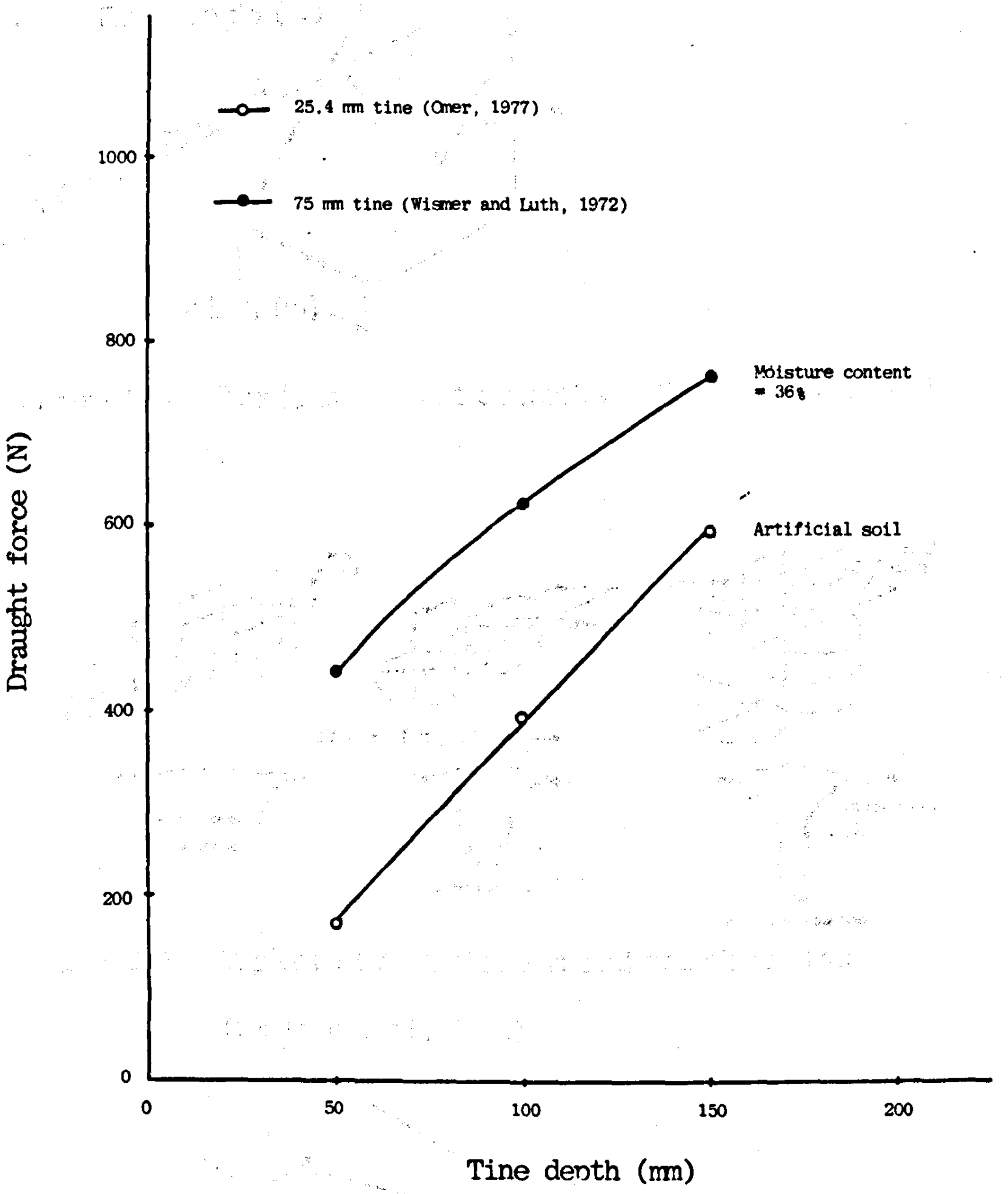


Figure 2.7 Relationship between draught force and tine depth (Data for 90° rake angle tines).

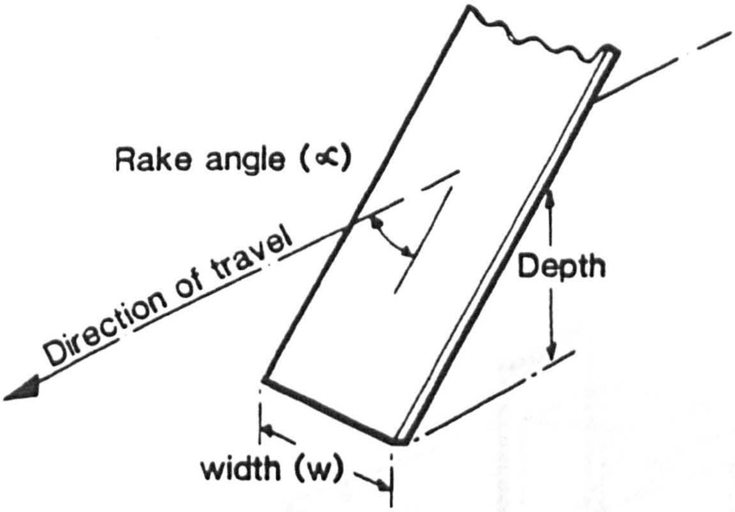


Figure 2.8 **Simple implement geometry** (Smith et. al, 1988)

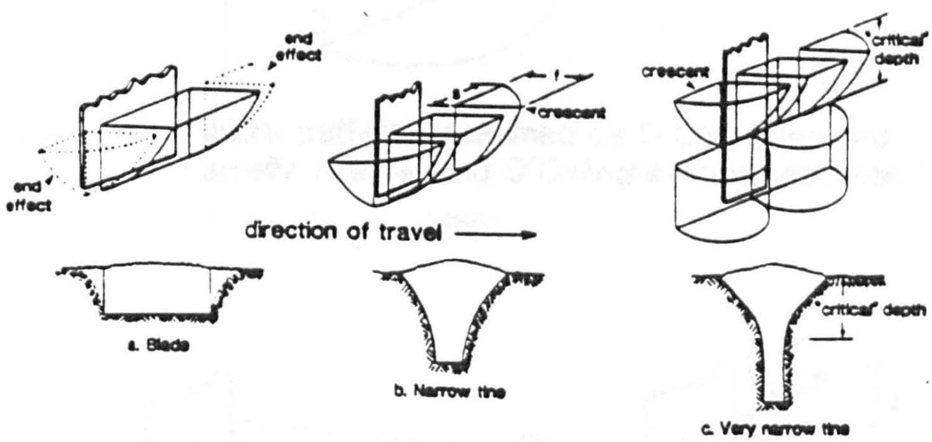


Figure 2.9 **Implement classification and soil disturbance**

(Smith et. al, 1988)

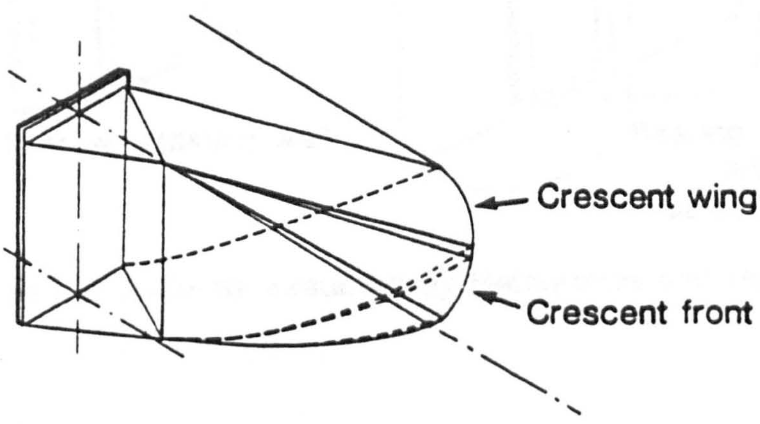


Figure 2.10 **Soil failure crescents assumed by Payne (1956)**

(Smith et. al, 1988)

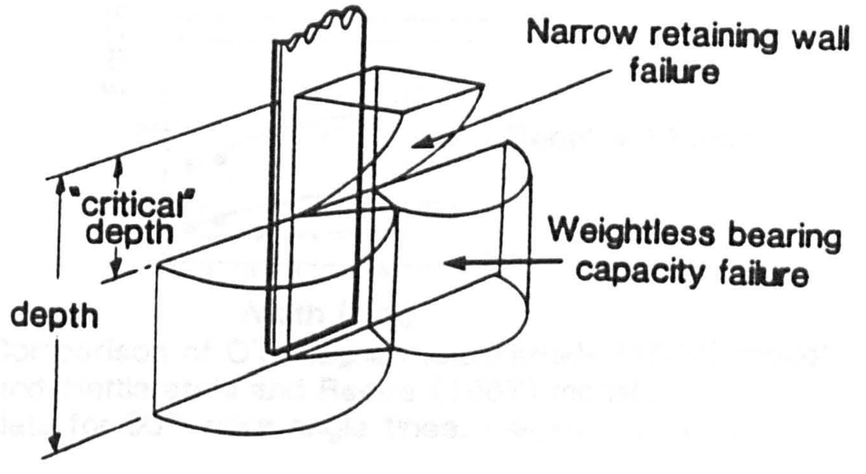


Figure 2.11 **Failure patterns assumed by O'Callaghan and Farrelly (1964) and O'Callaghan and McCullen (1965)** (Smith et. al, 1988)

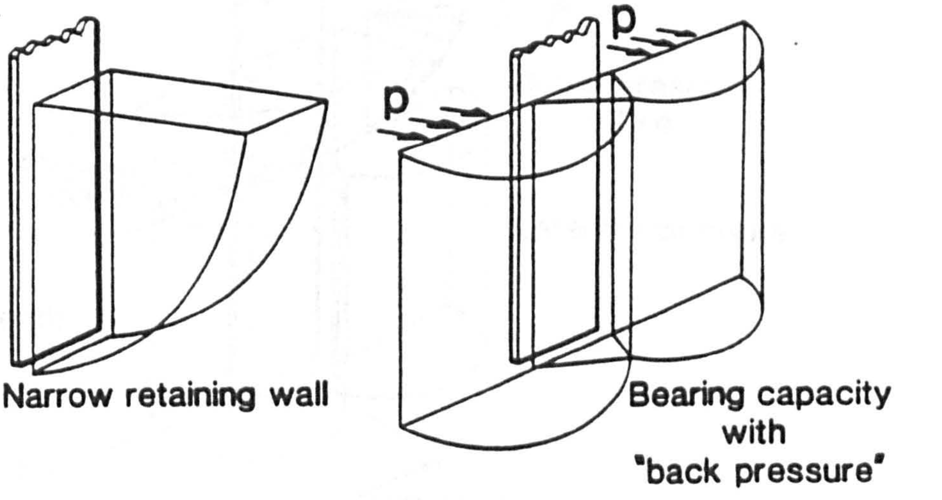


Figure 2.12 **Failure patterns assumed by Hettiaratchi and Reece (1967)** (Smith et. al, 1988)

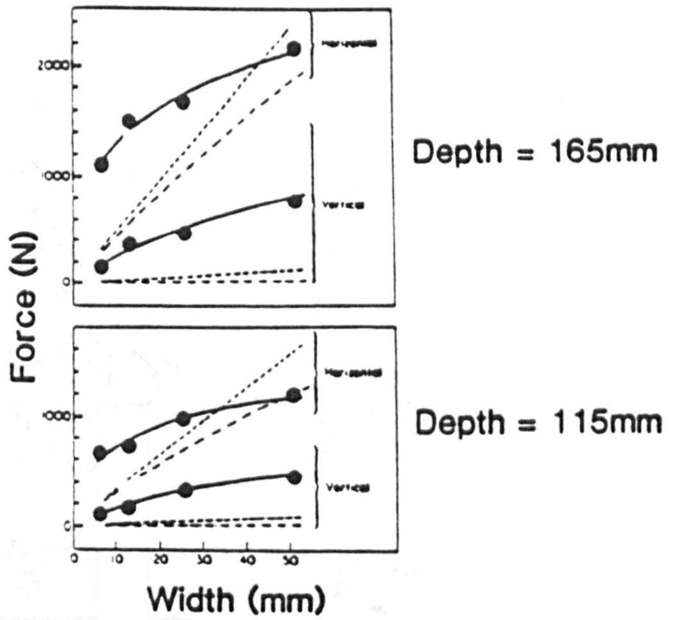


Figure 2.13. **Comparison of O'Callaghan and Farrelly (1964) model and Hettiaratchi and Reece (1967) model : data for 90° rake angle tines.** (Smith et. al, 1988)

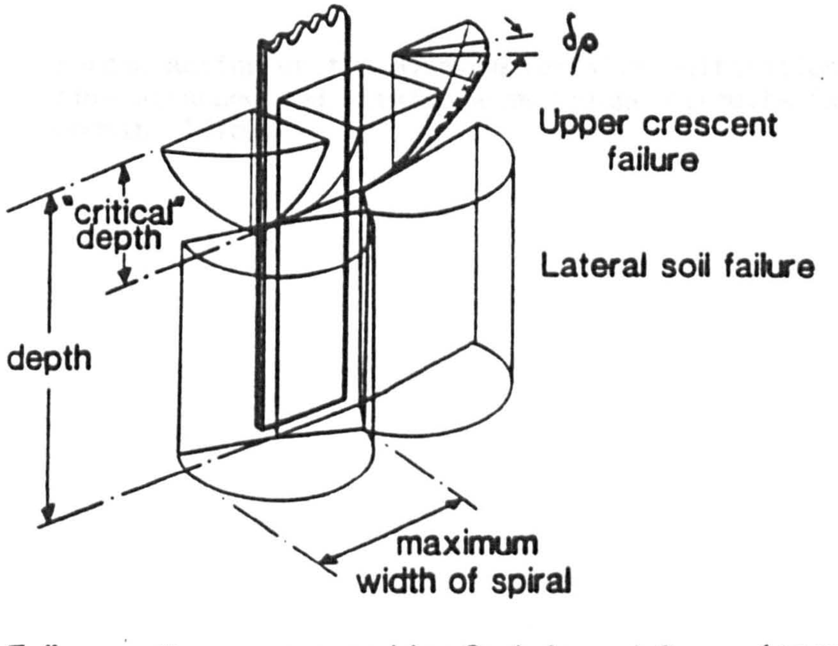


Figure 2.14 **Failure patterns assumed by Godwin and Spoor (1977)**

(Smith et. al, 1988)

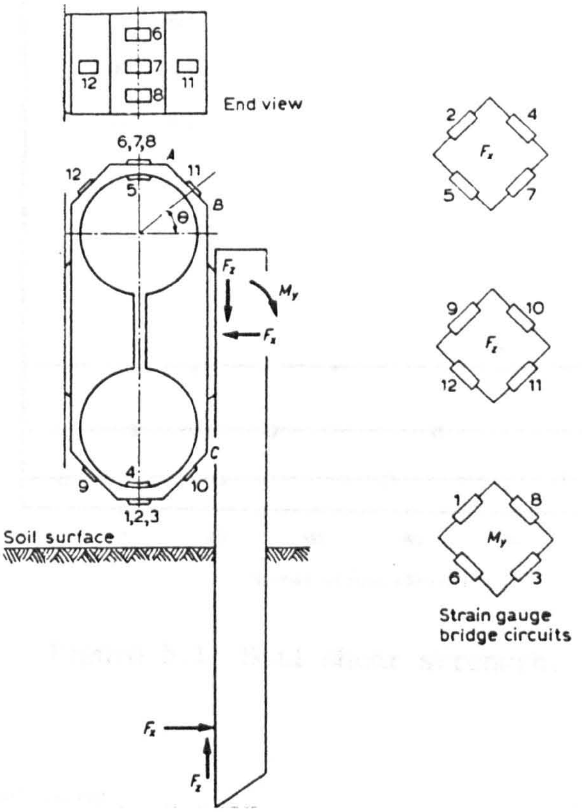


Figure 4.1 Forces acting on the dynamometer with cultivation tine attached and strain gauge bridge circuits (after Godwin, 1975).

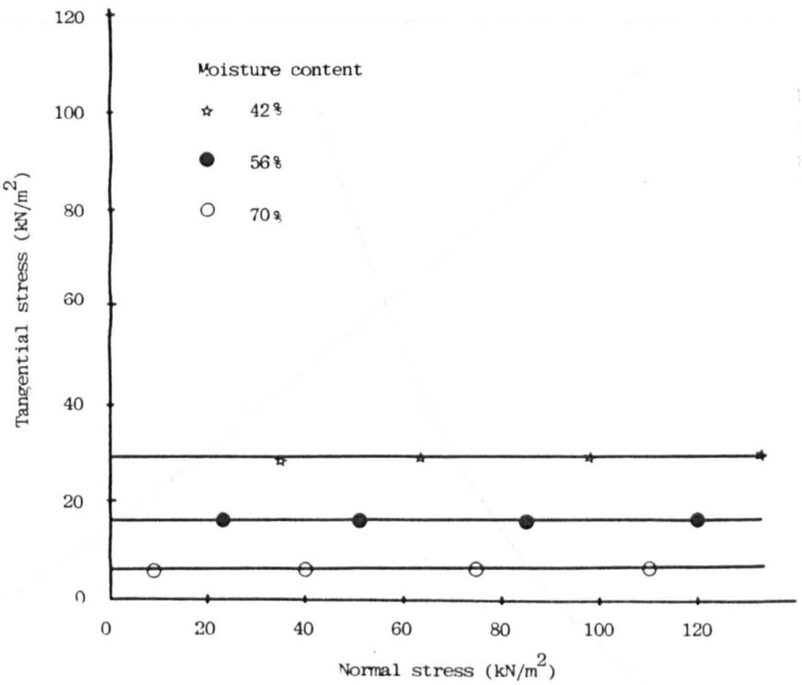


Figure 5.1 Soil shear strength.

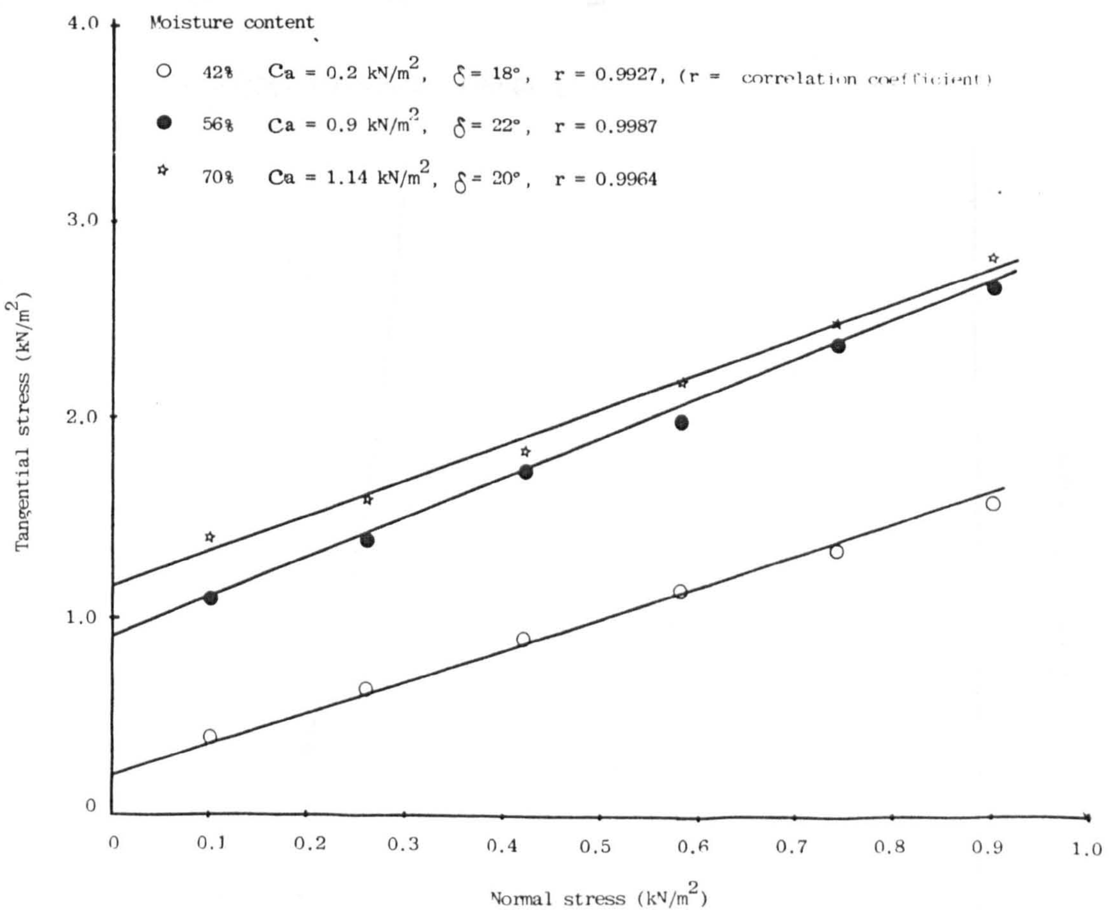


Figure 5.2 Soil-metal shearing resistance

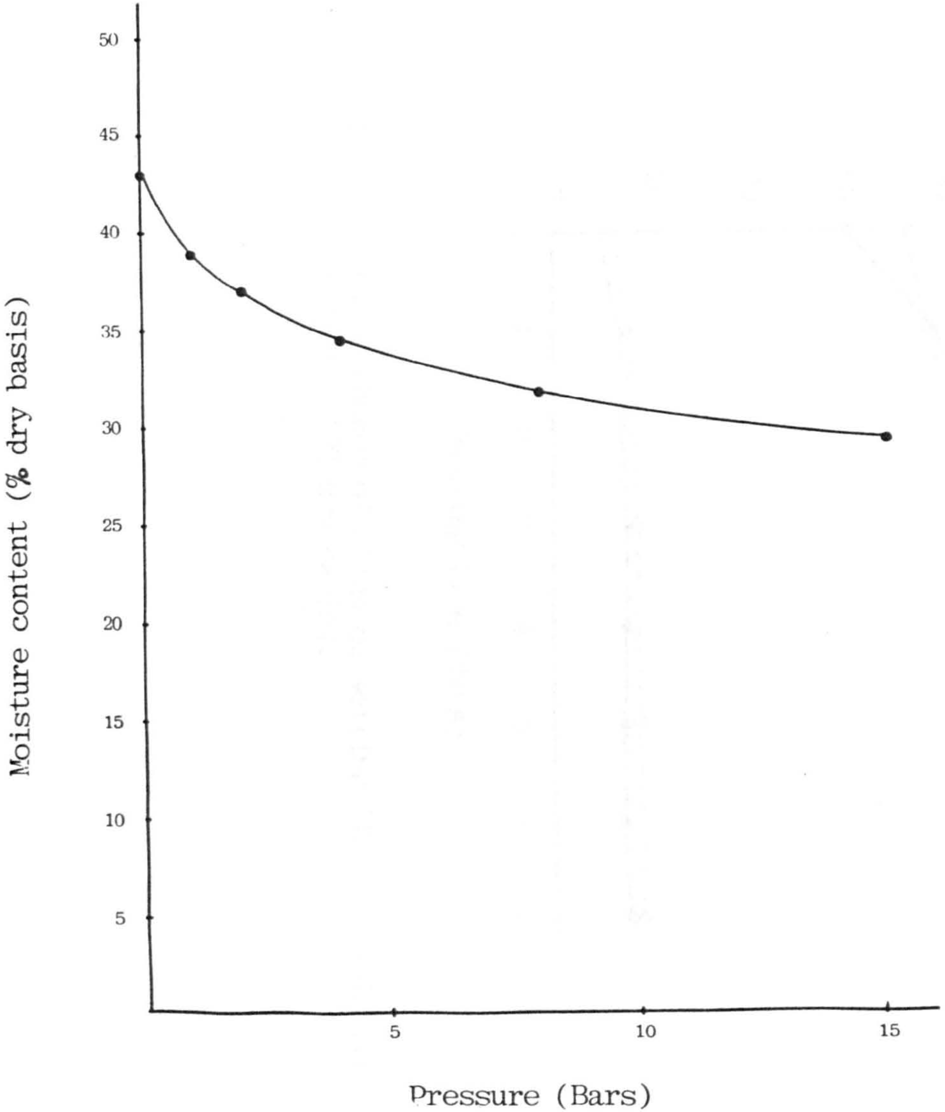


Figure 5.3 Water retention characteristics.

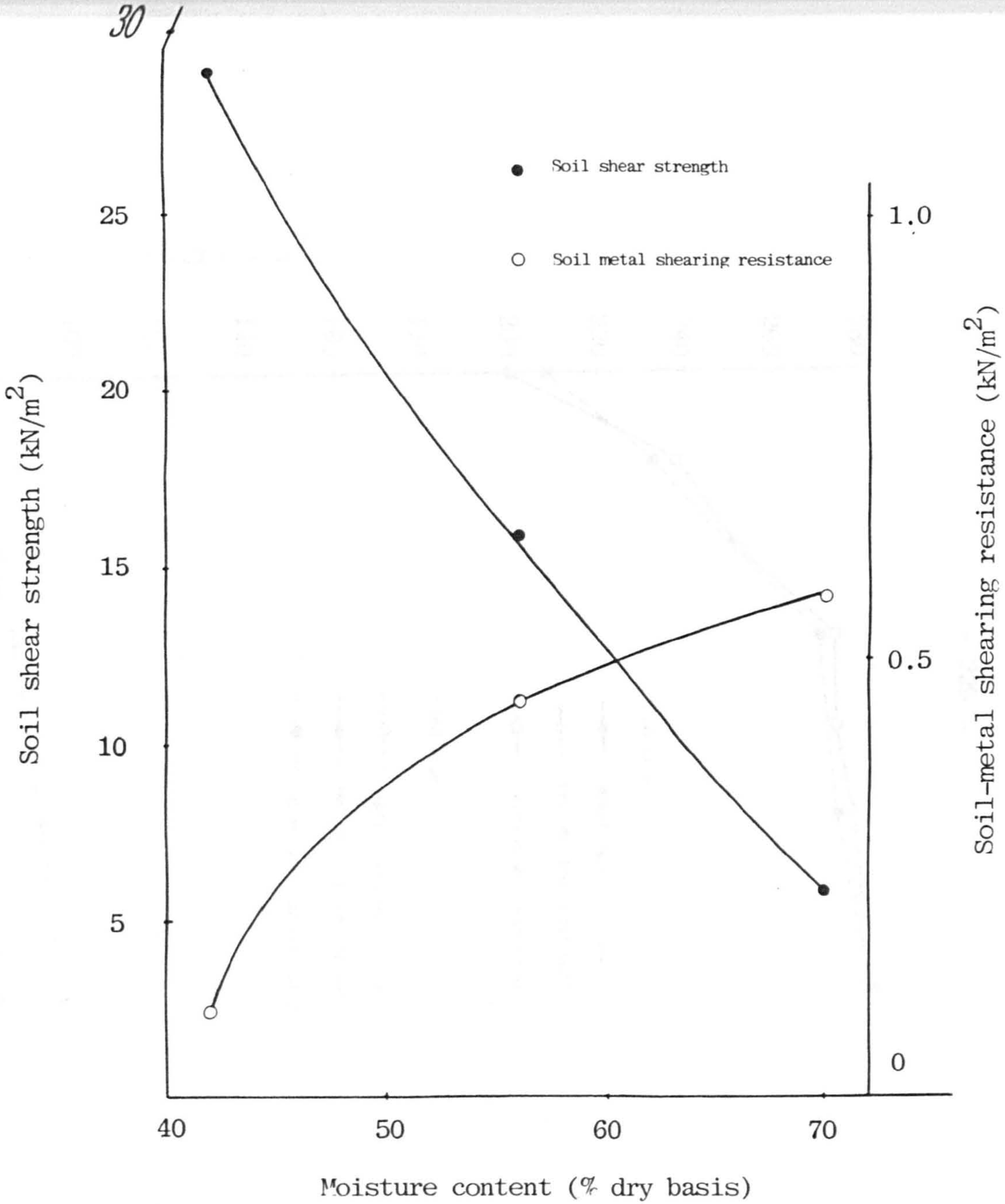


Figure 5.4 Relationships between soil shear strength and soil-metal shearing resistance with moisture content.

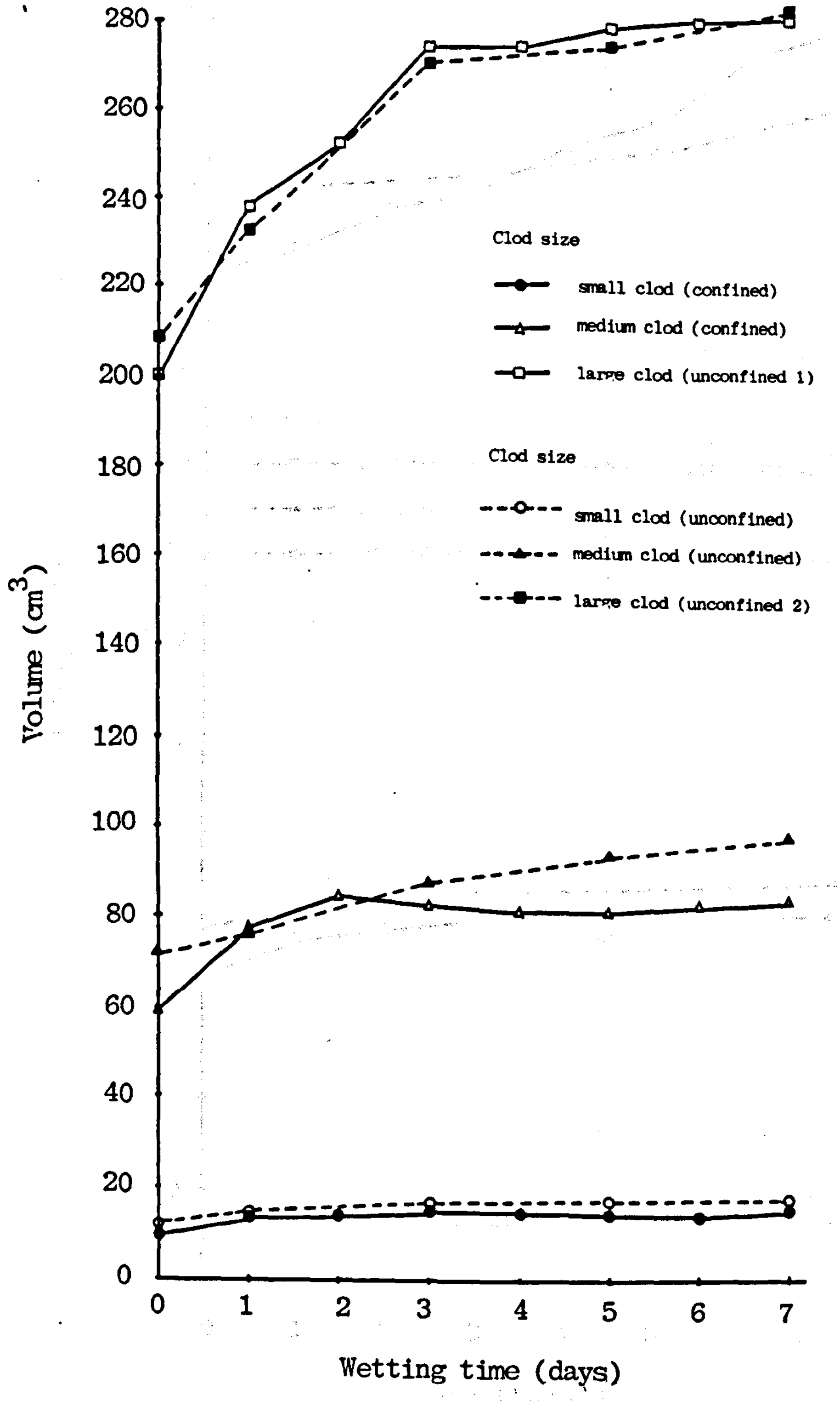


Figure 5.5 Volume change of clods on wetting (Initial moisture content = 12% dry basis).

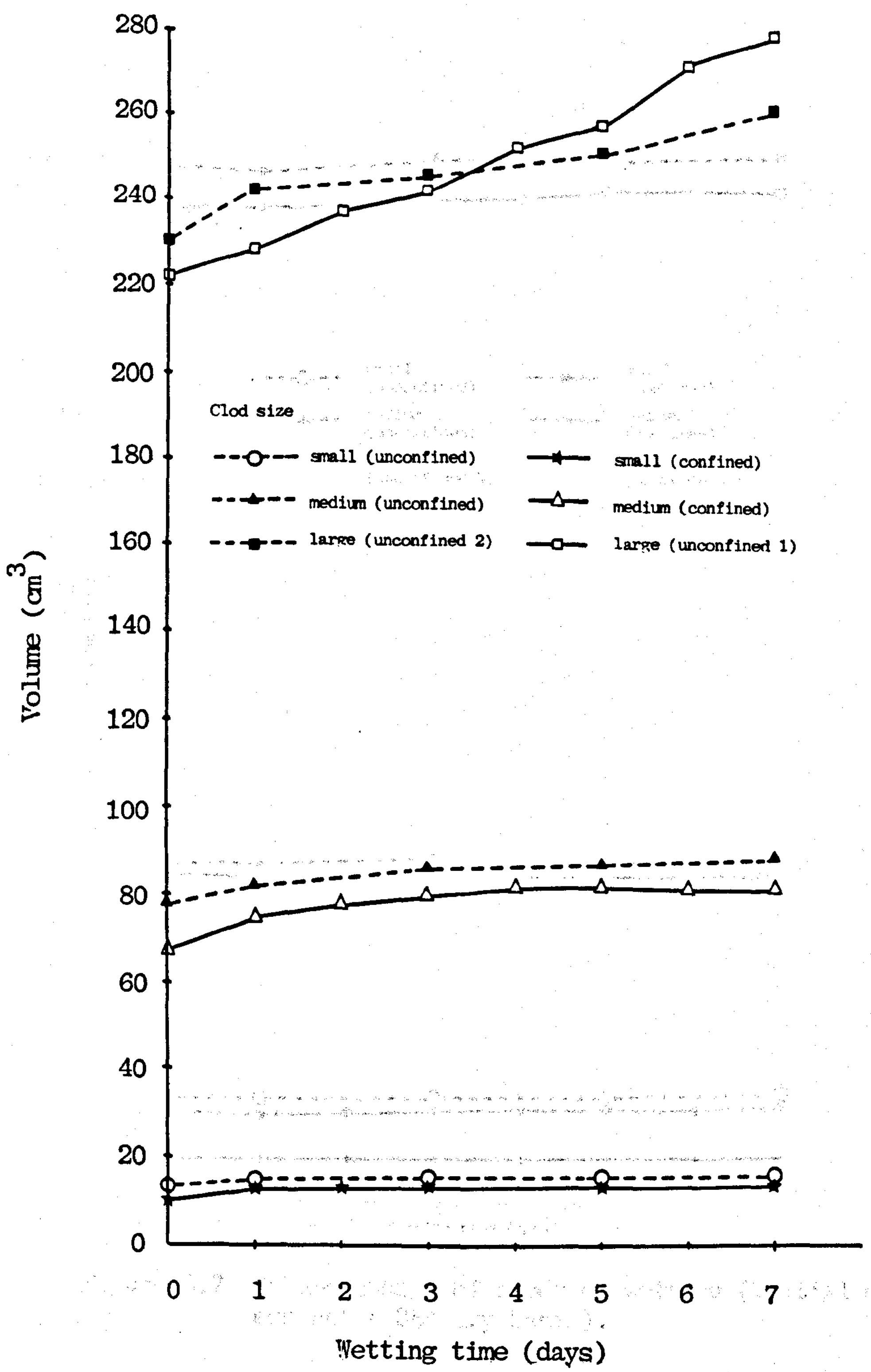


Figure 5.6 Volume change of clods on wetting (Initial moisture content = 22% dry basis).

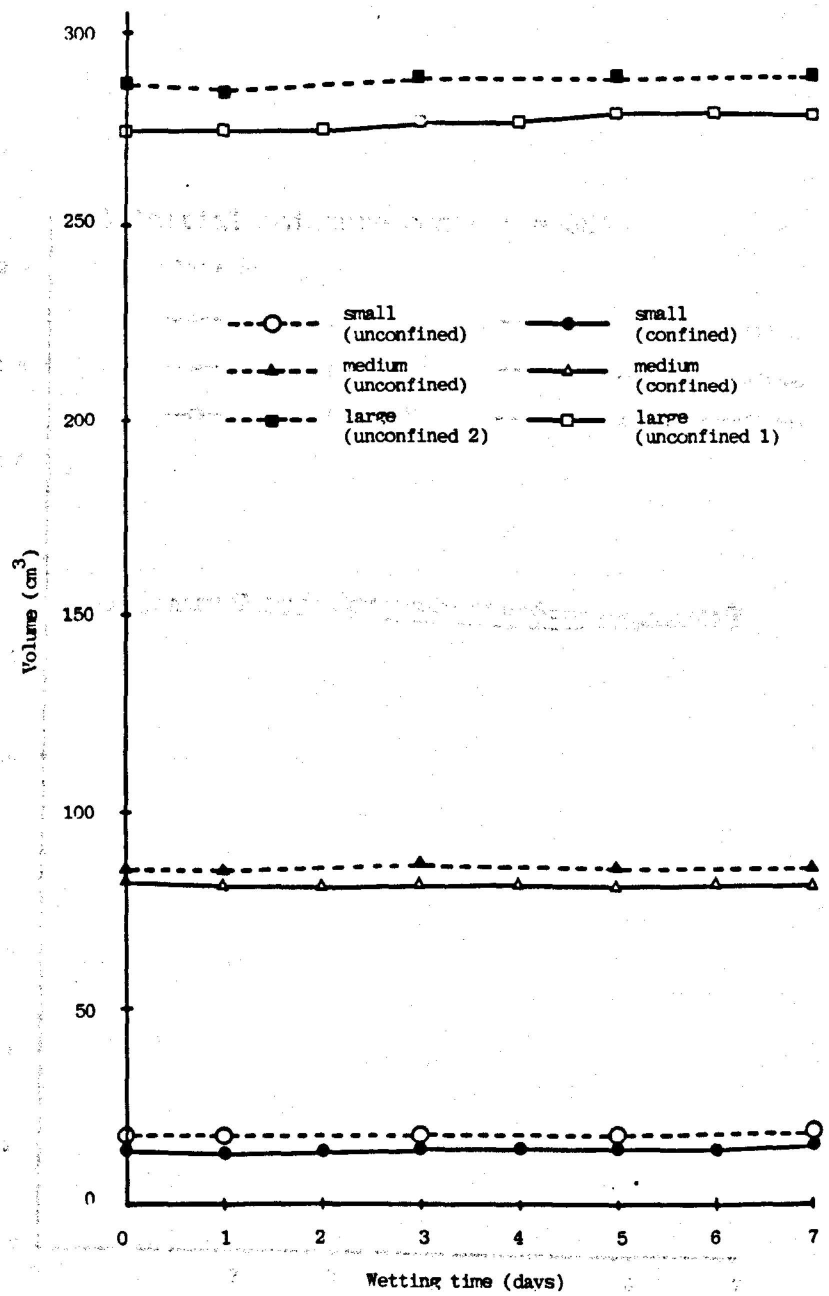
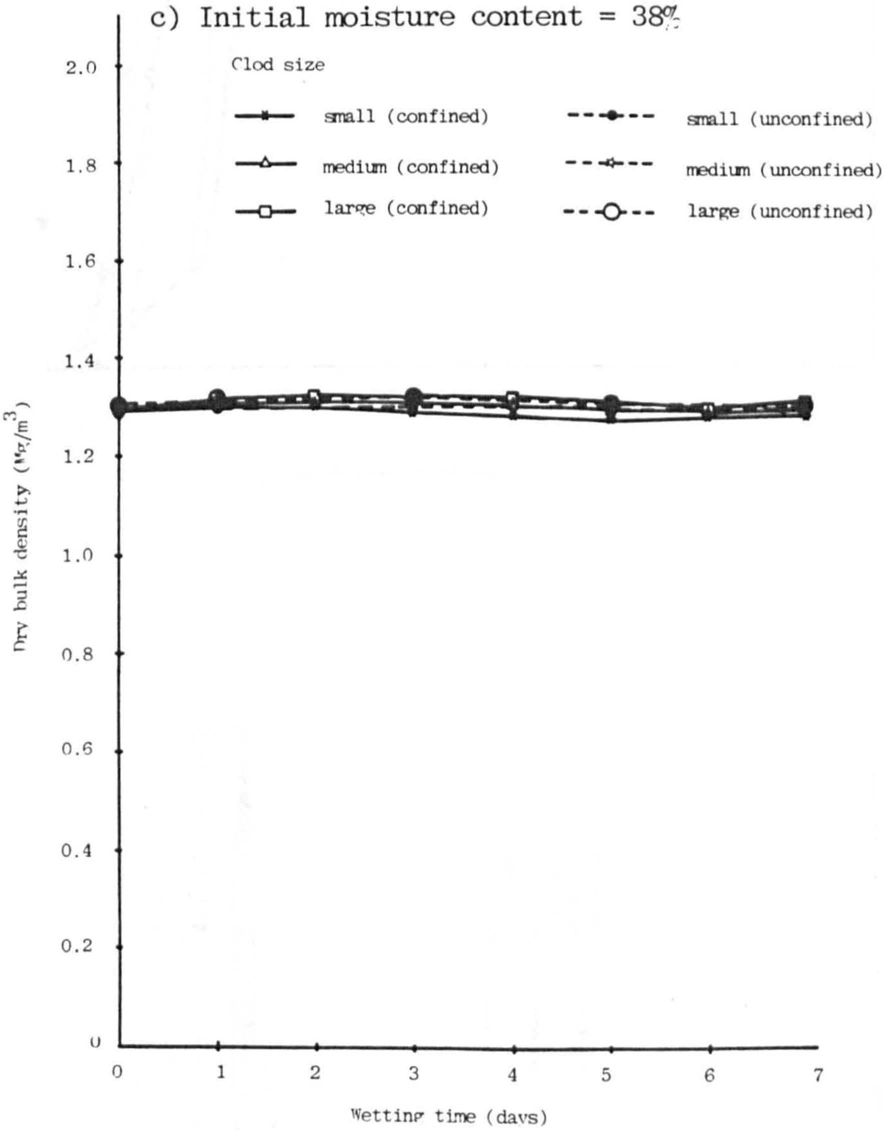


Figure 5.7 Volume change of clods on wetting (Initial moisture content = 38% dry basis).


c) Initial moisture content = 38%
Clod size
small (confined)
small (unconfined)
medium (confined)
medium (unconfined)
large (confined)
large (unconfined)
Dry bulk density (Mg/m3)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
Wetting time (days)

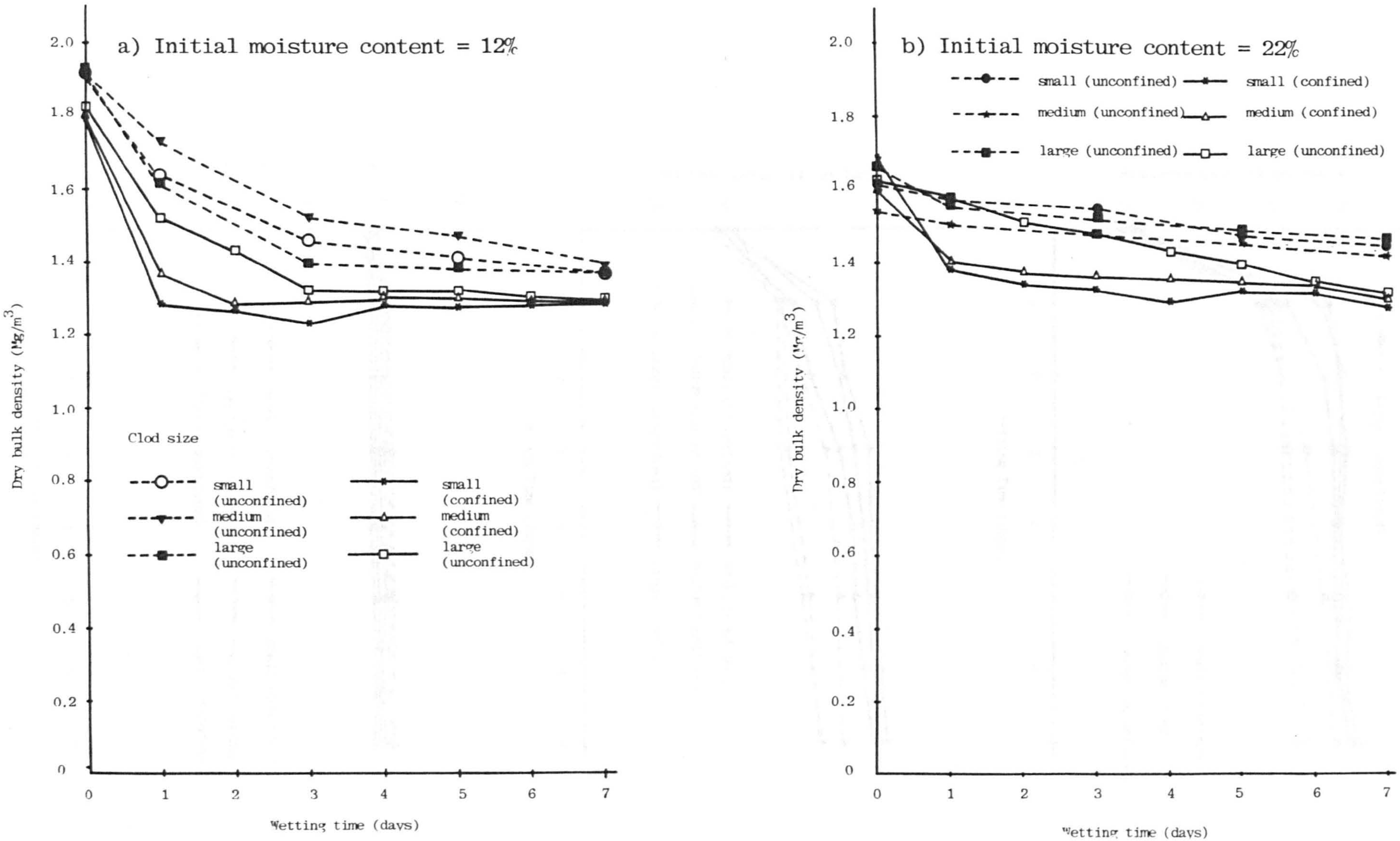


Figure 5.8 Dry bulk density change of clods on wetting

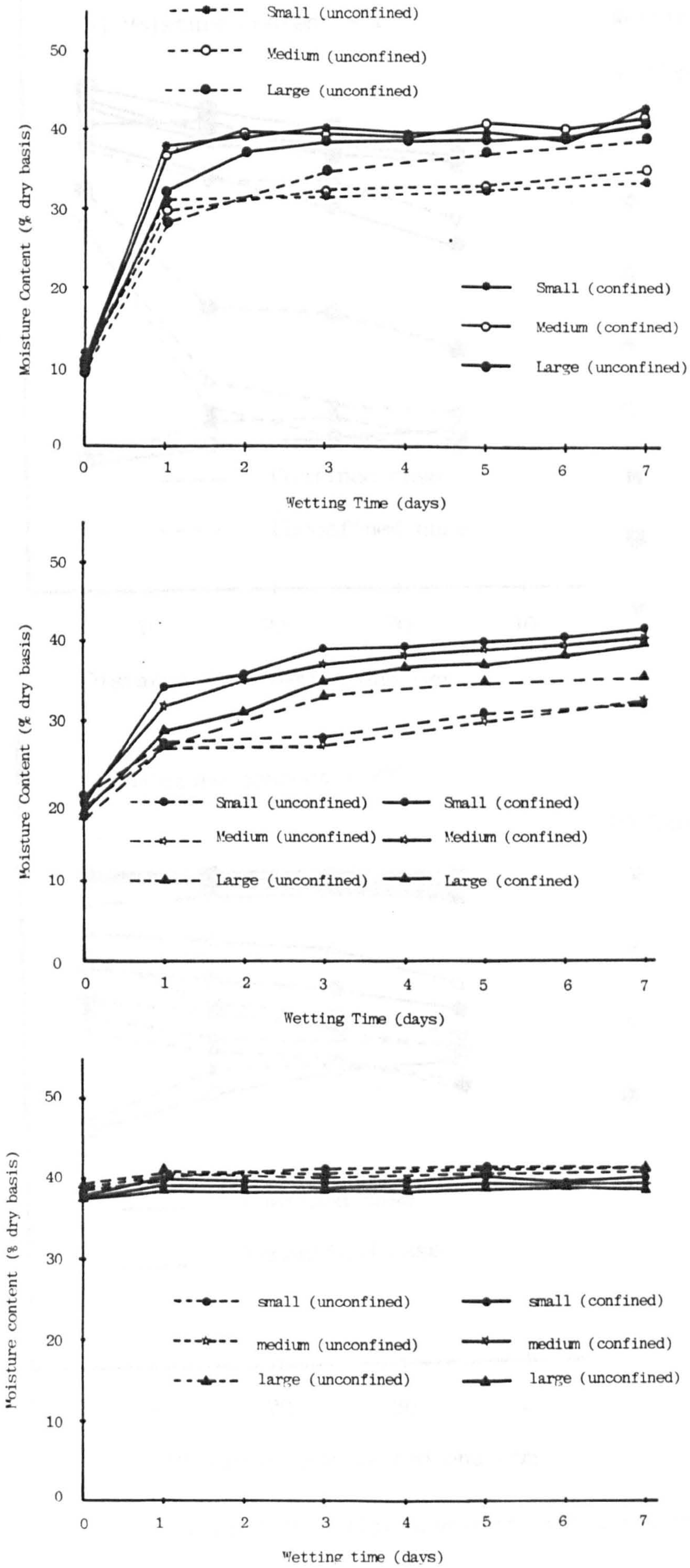
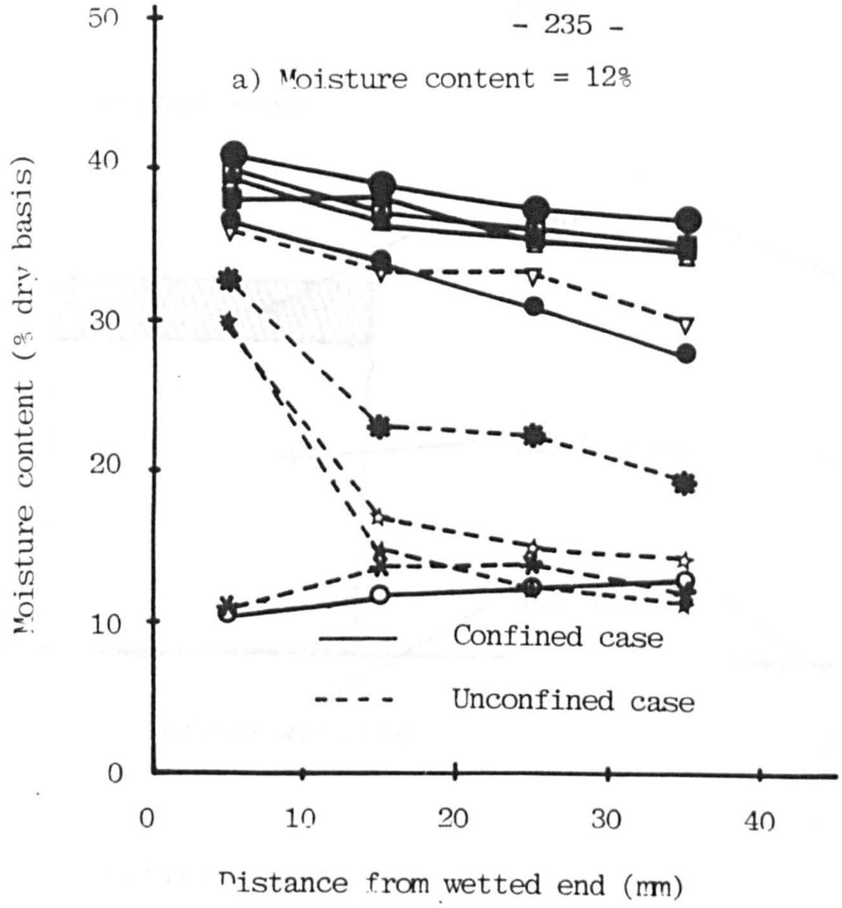


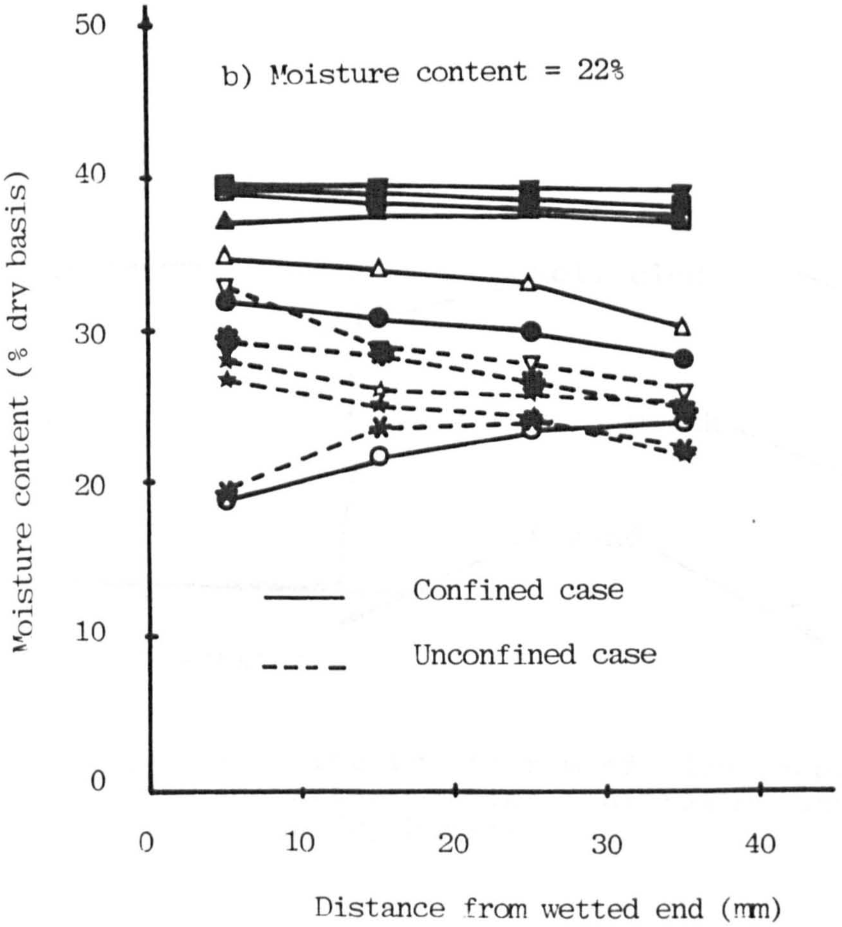
Figure 5.9 Rate of water uptake by clods on wetting (Initial moisture content: top = 12%, middle = 22%, bottom = 38%).



Wetting period (days)

a) Confined case

Symbol	Days
○	0
●	1
△	2
▲	3
□	4
■	5
⬤	6
▼	7

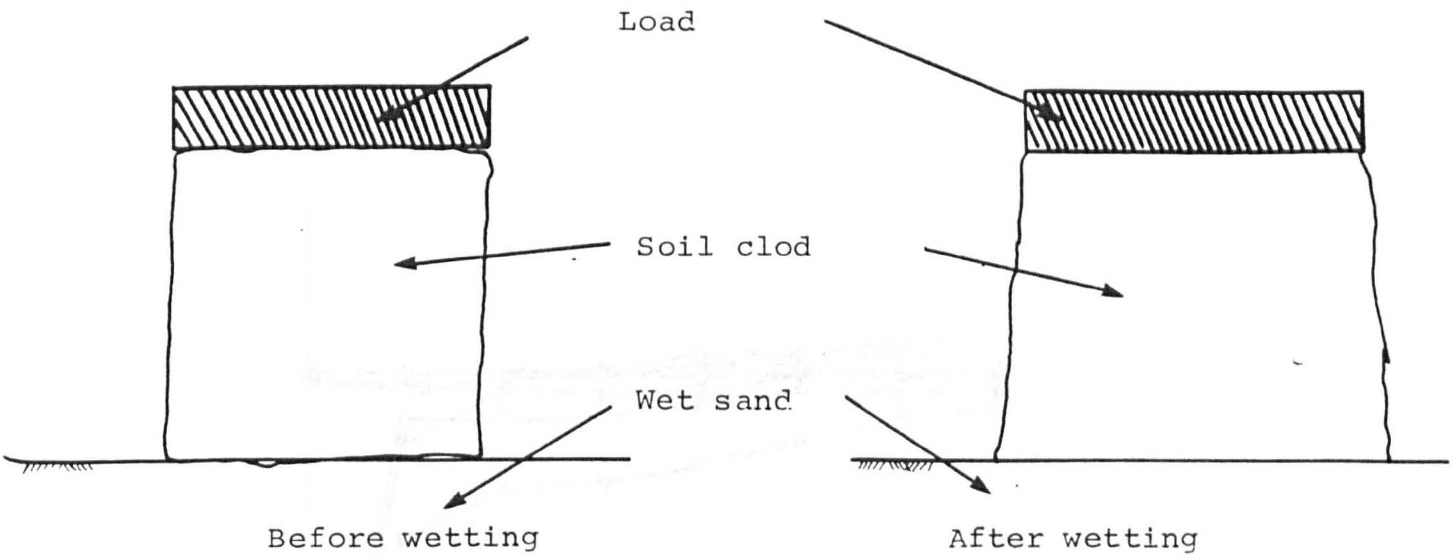


b) Unconfined case

Symbol	Days
✱	0
★	1
☆	3
✸	5
▽	7

Figure 5.10 Moisture profile within a medium clod after wetting.

(a) Confined case



(b) Unconfined case

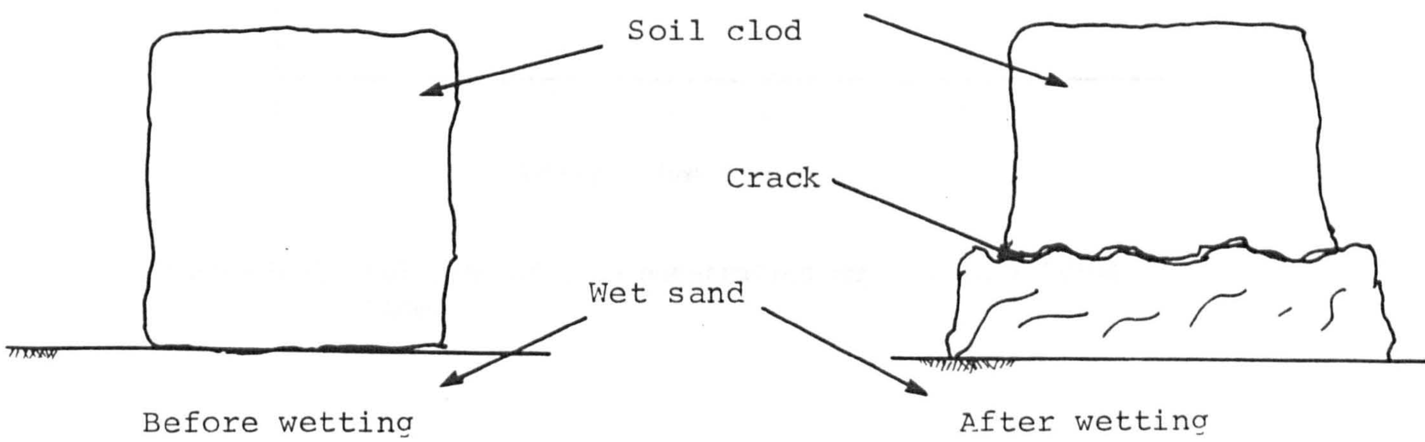


Figure 5.10i A schematic diagram of clod shape before and after wetting (initial moisture content = 12% dry basis).

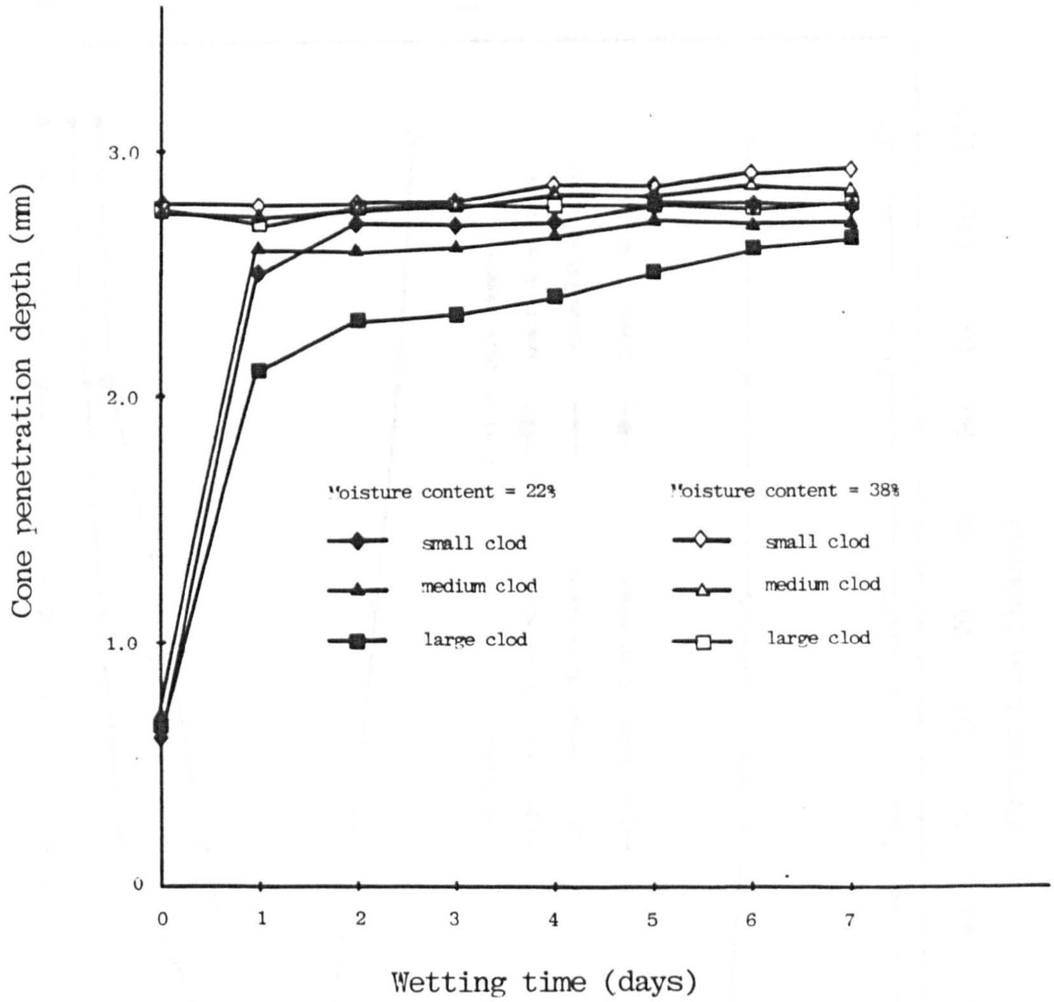


Figure 5.11 Relation of cone penetration depth with wetting time.

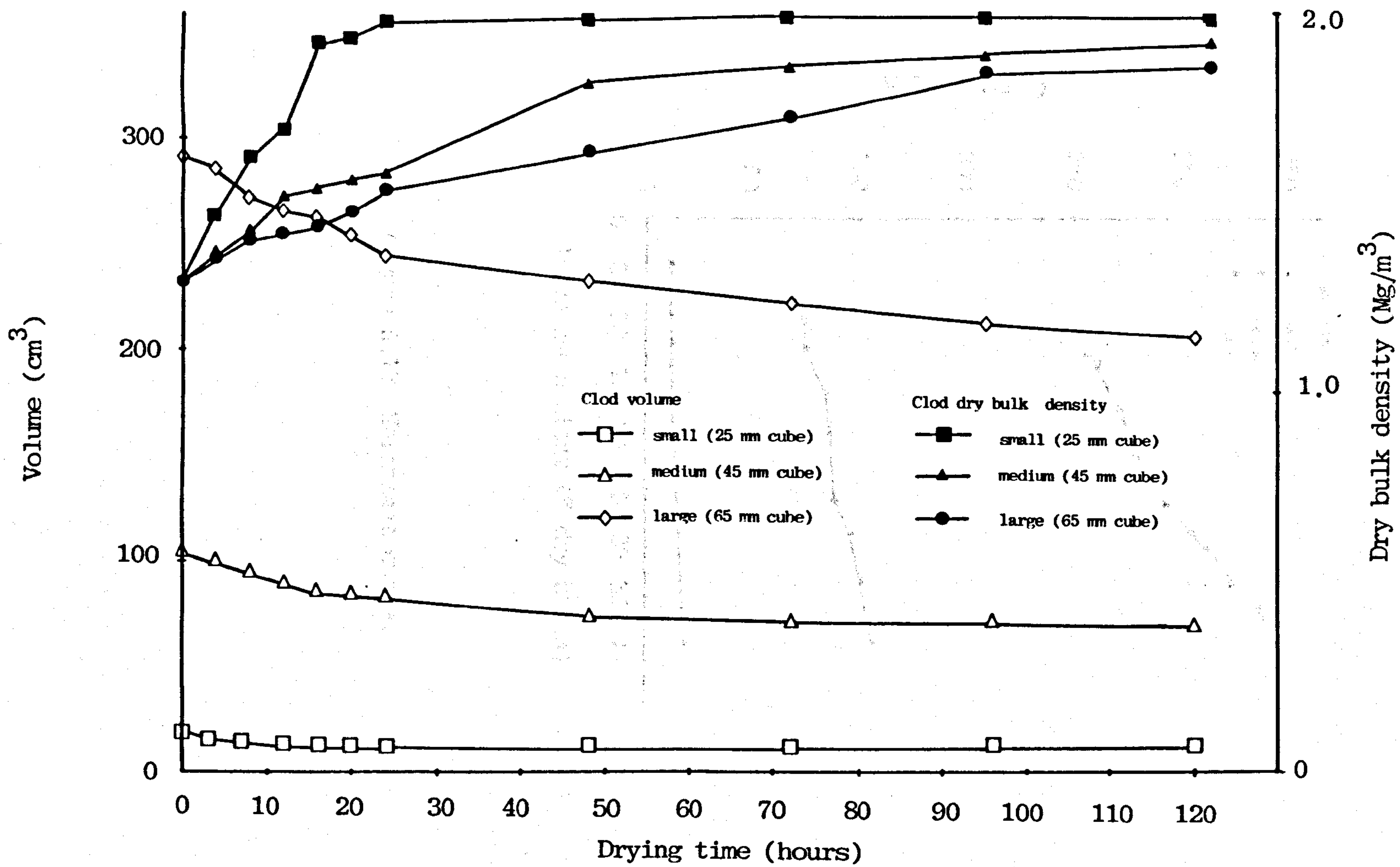


Figure 5.12 Relation of clod volume and dry bulk density with drying time.

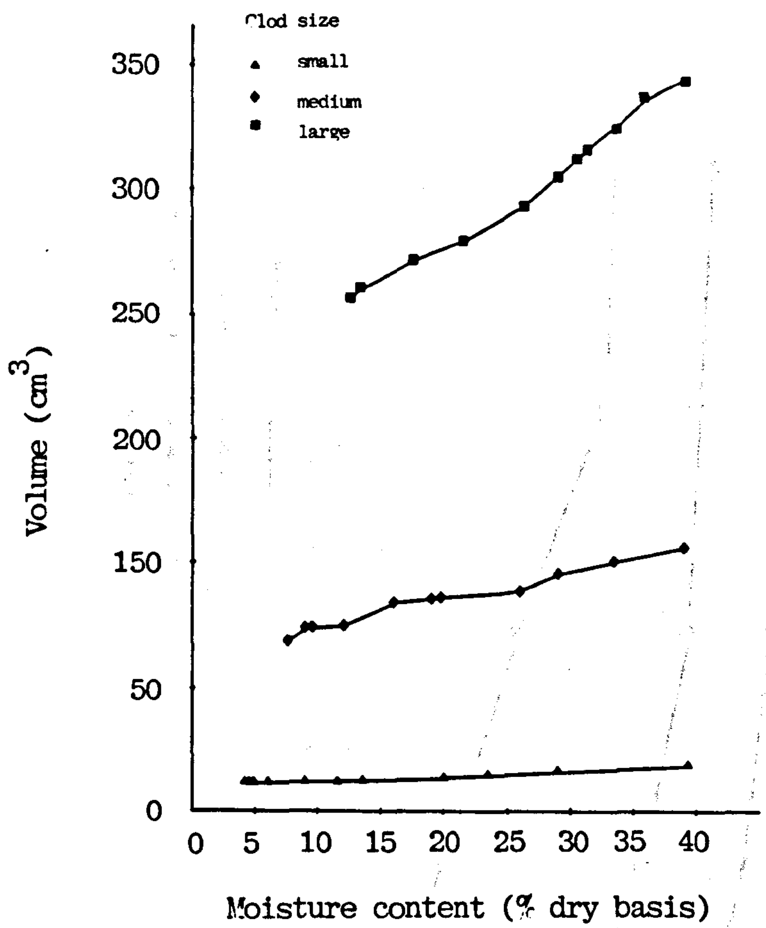


Figure 5.13 Shrinkage curve.

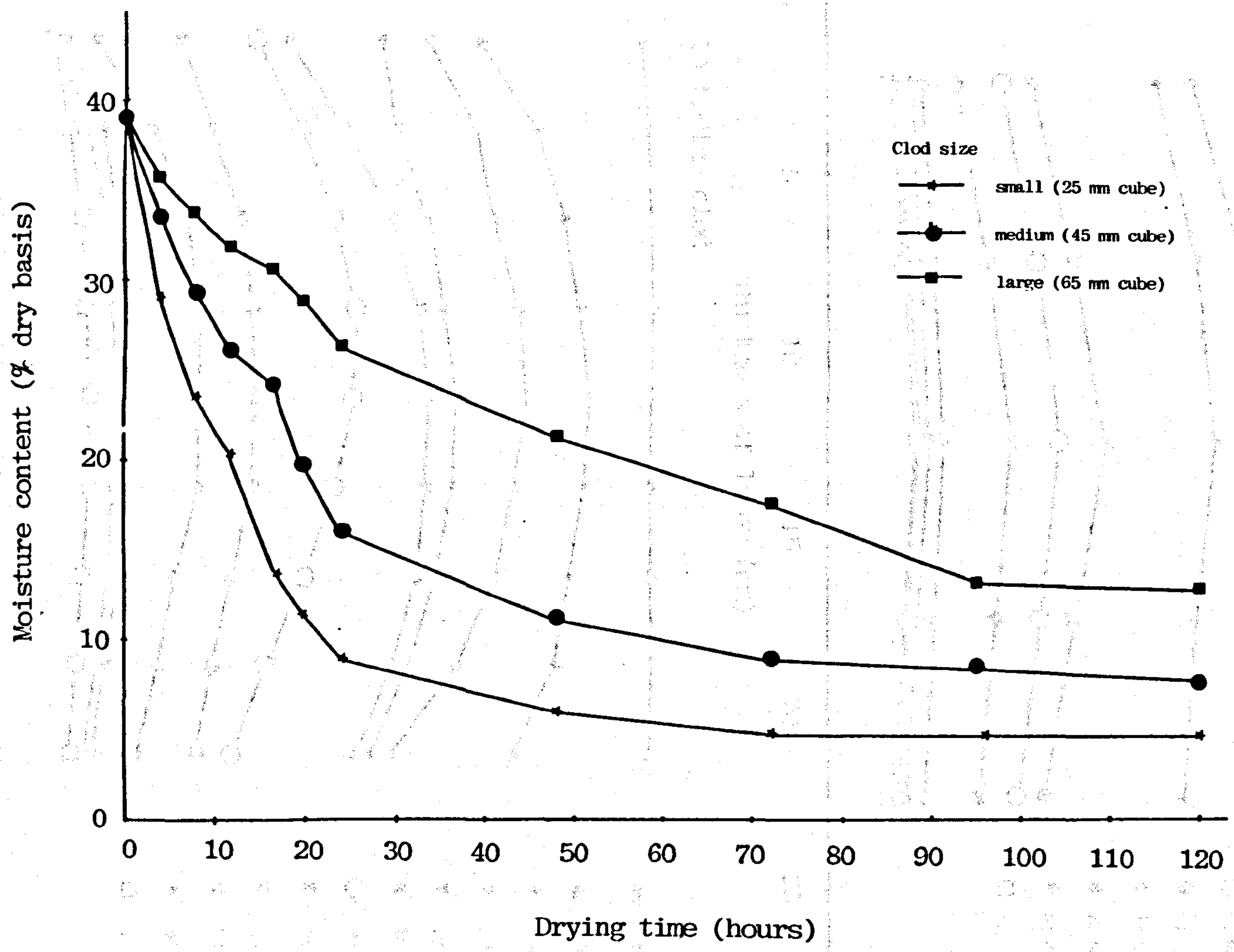


Figure 5.14 Relation of clod moisture content with drying time (Drying temperature = 25°C on top of an oven.

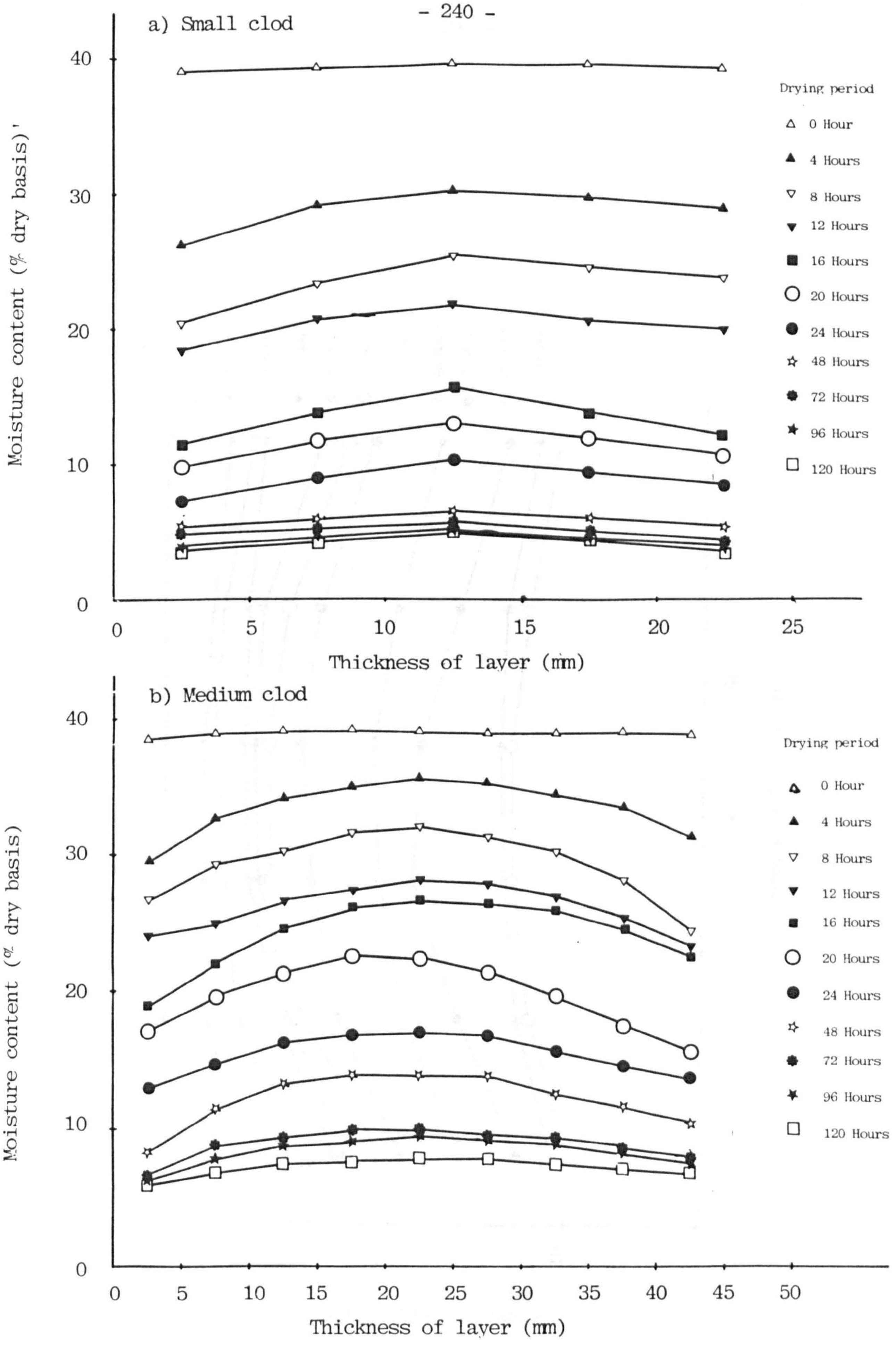


Figure 5.15 Moisture gradients within clods on drying (Drying temperature = 25°C on top of an oven).

c) Large clod

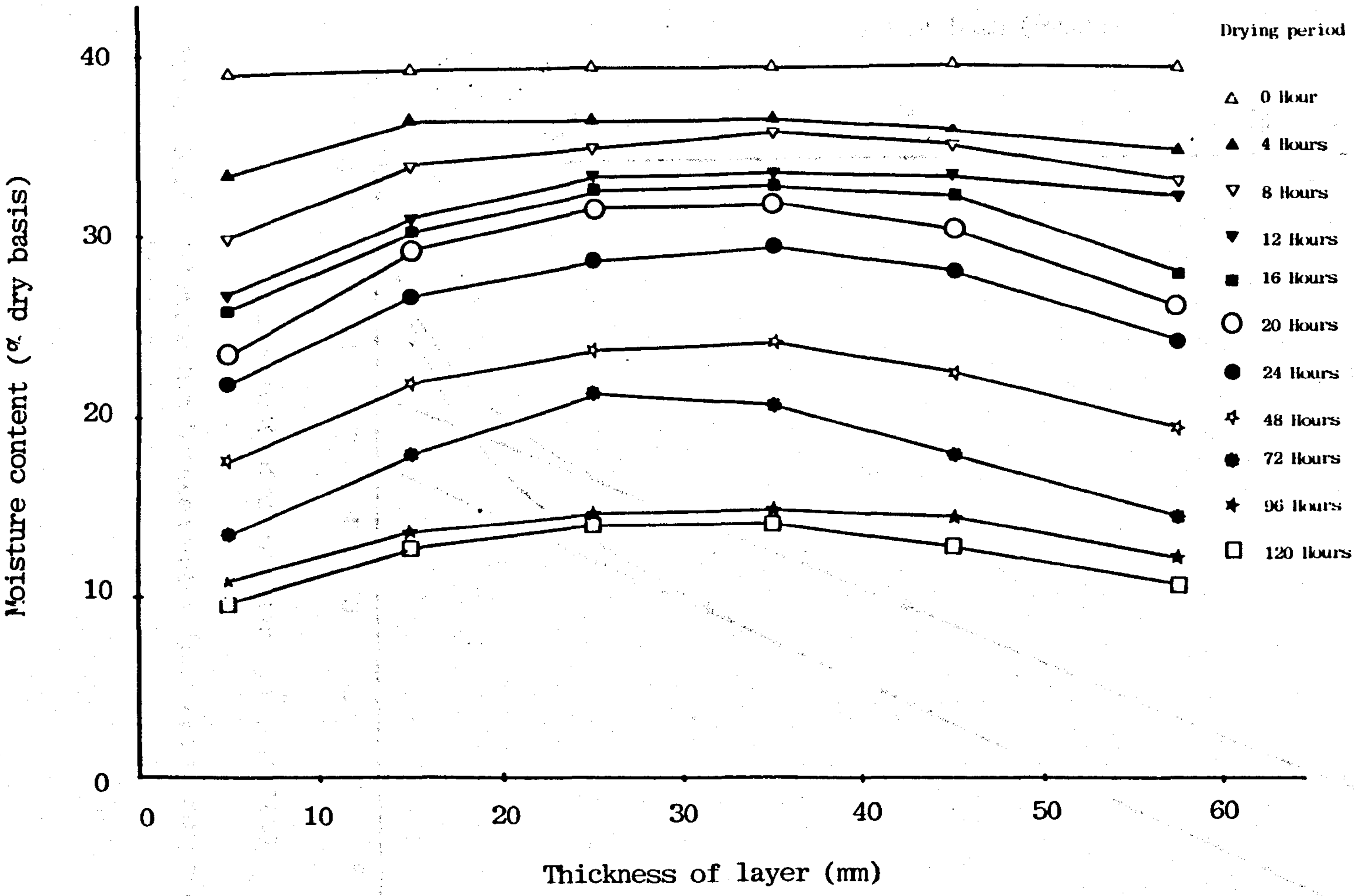


Figure 5.15 (continued).

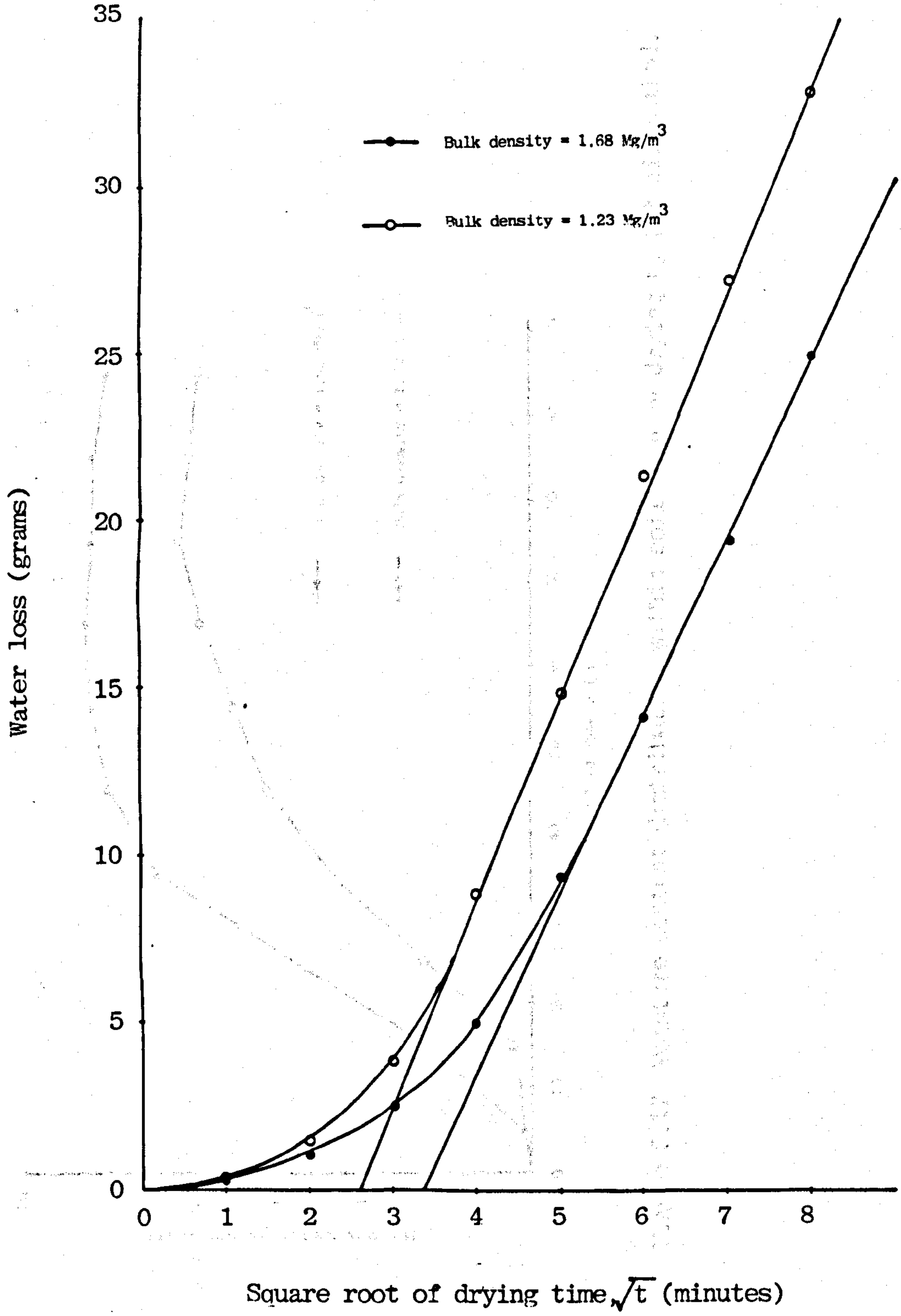


Figure 5.16 Relationship between water loss and square root of drying time.

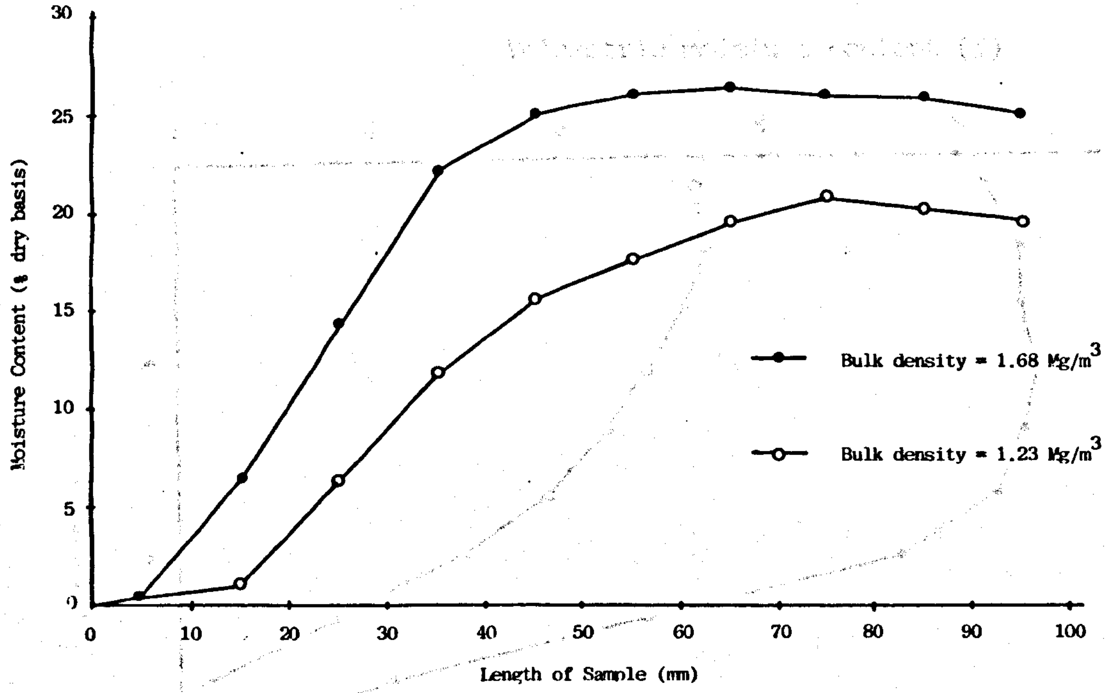


Figure 5.17 Moisture content distribution within soil core on drying by hot air method.

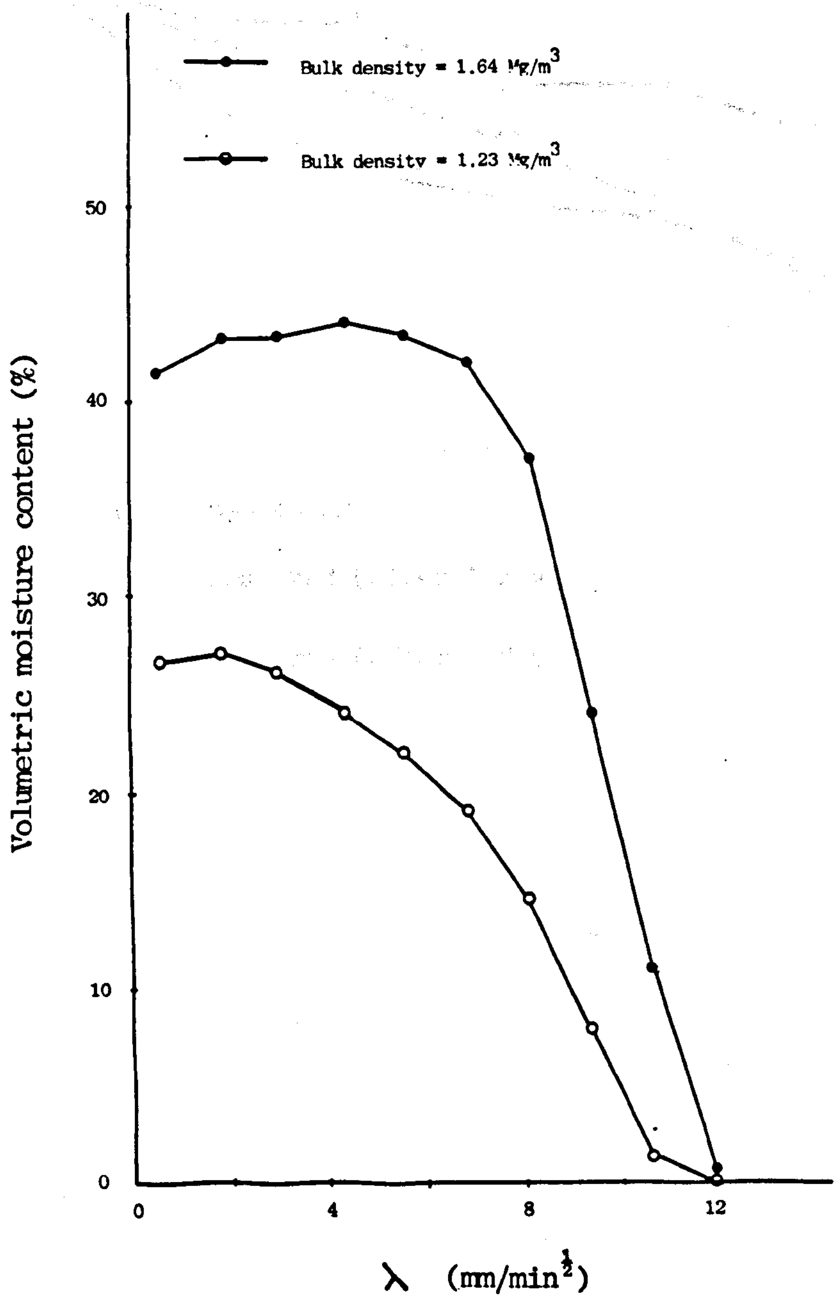


Figure 5.18 Relationship between volumetric moisture content and λ

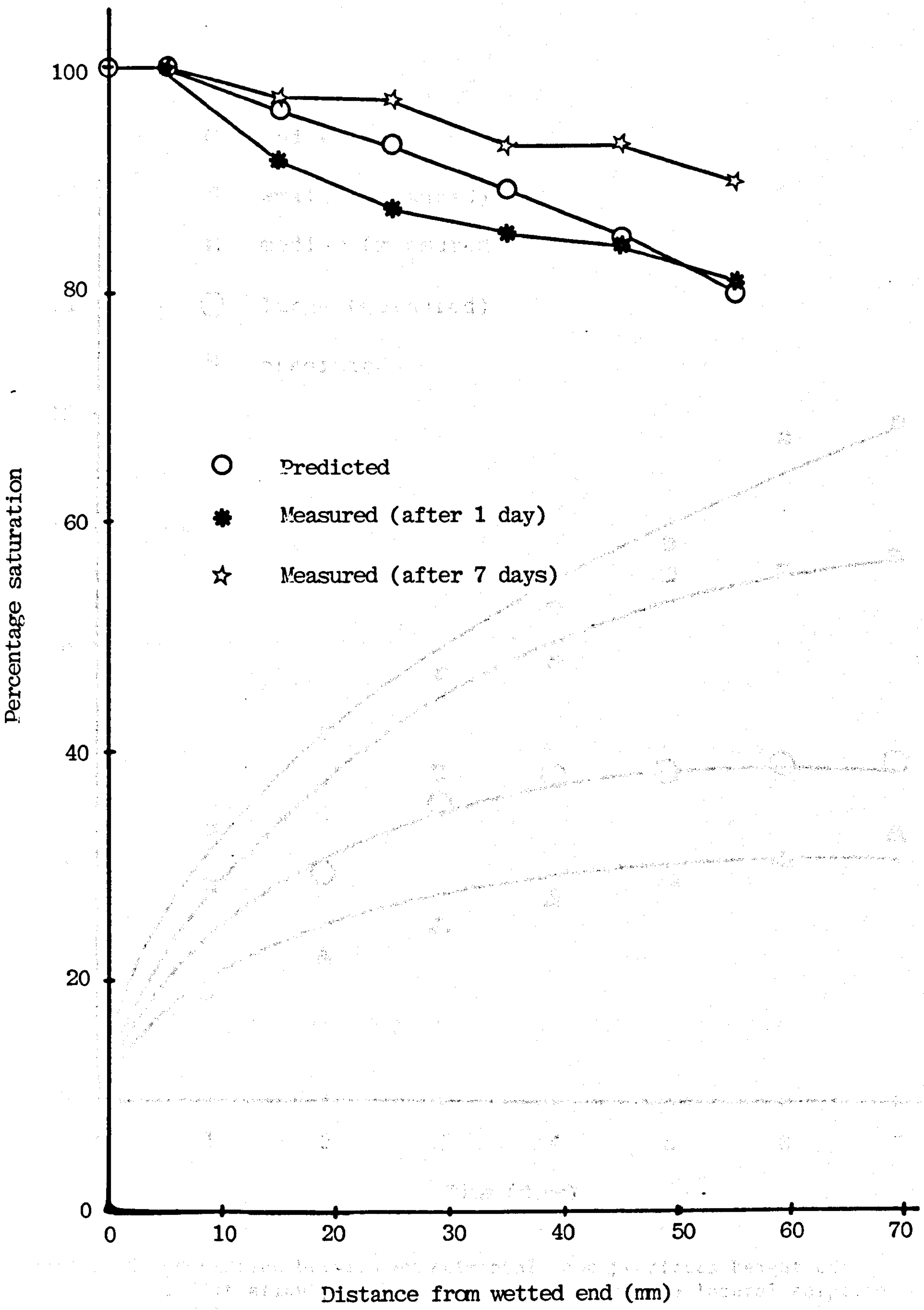


Figure 5.19 Comparison between experimental and predicted results (Linear heat flow model).

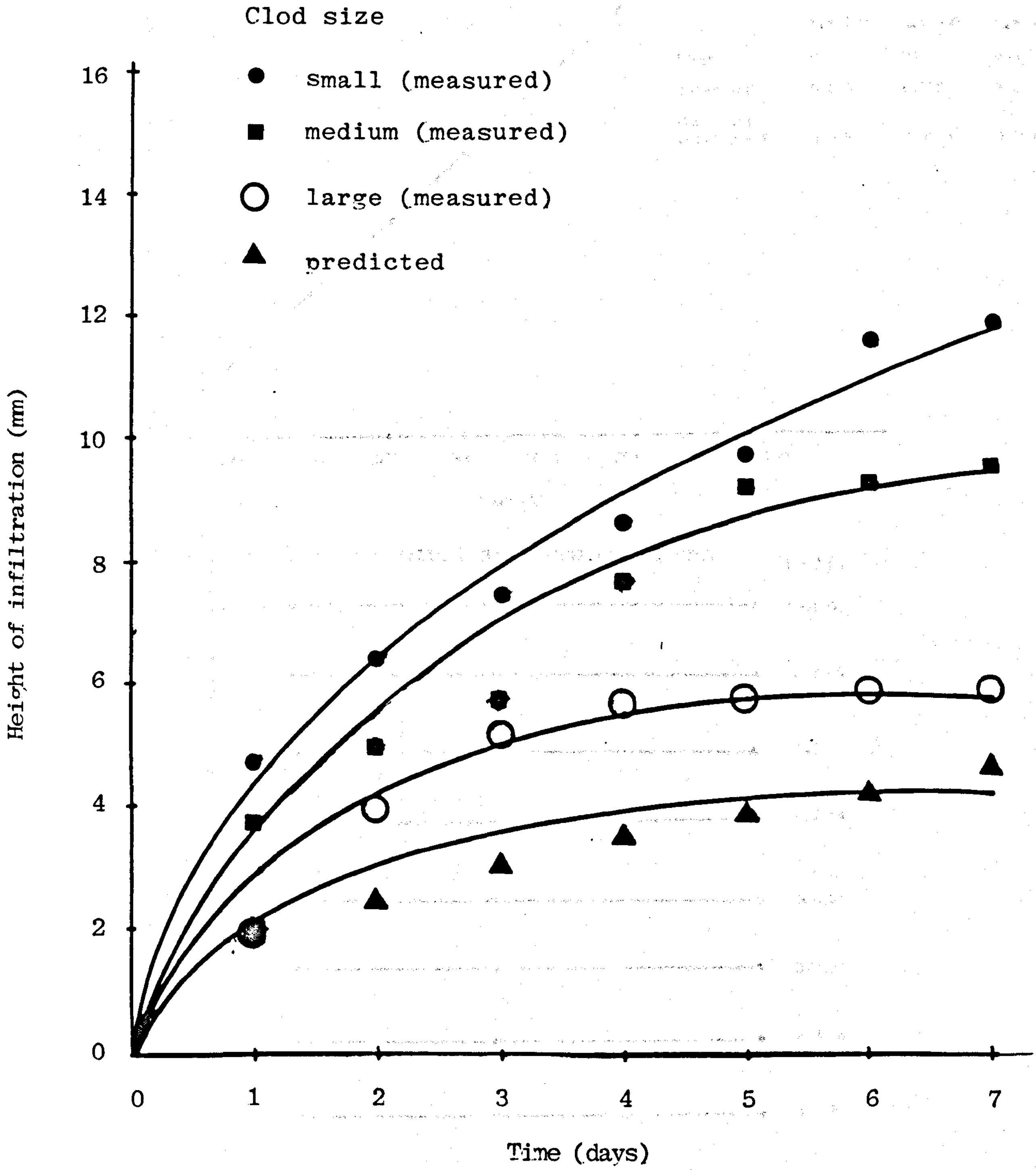


Figure 5.20 Comparison between experimental and predicted height of infiltration for three clod sizes using the lateral sorption model.

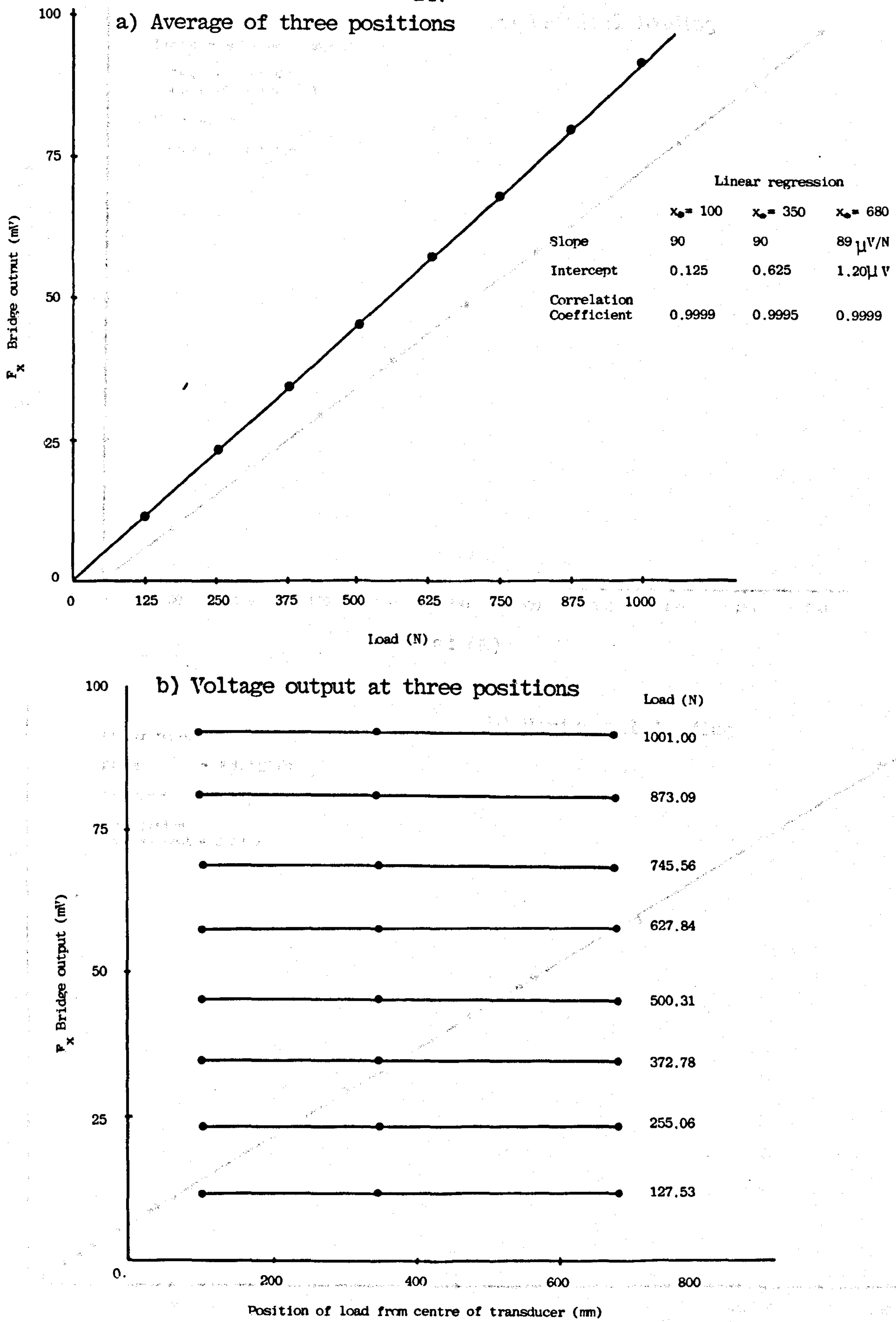
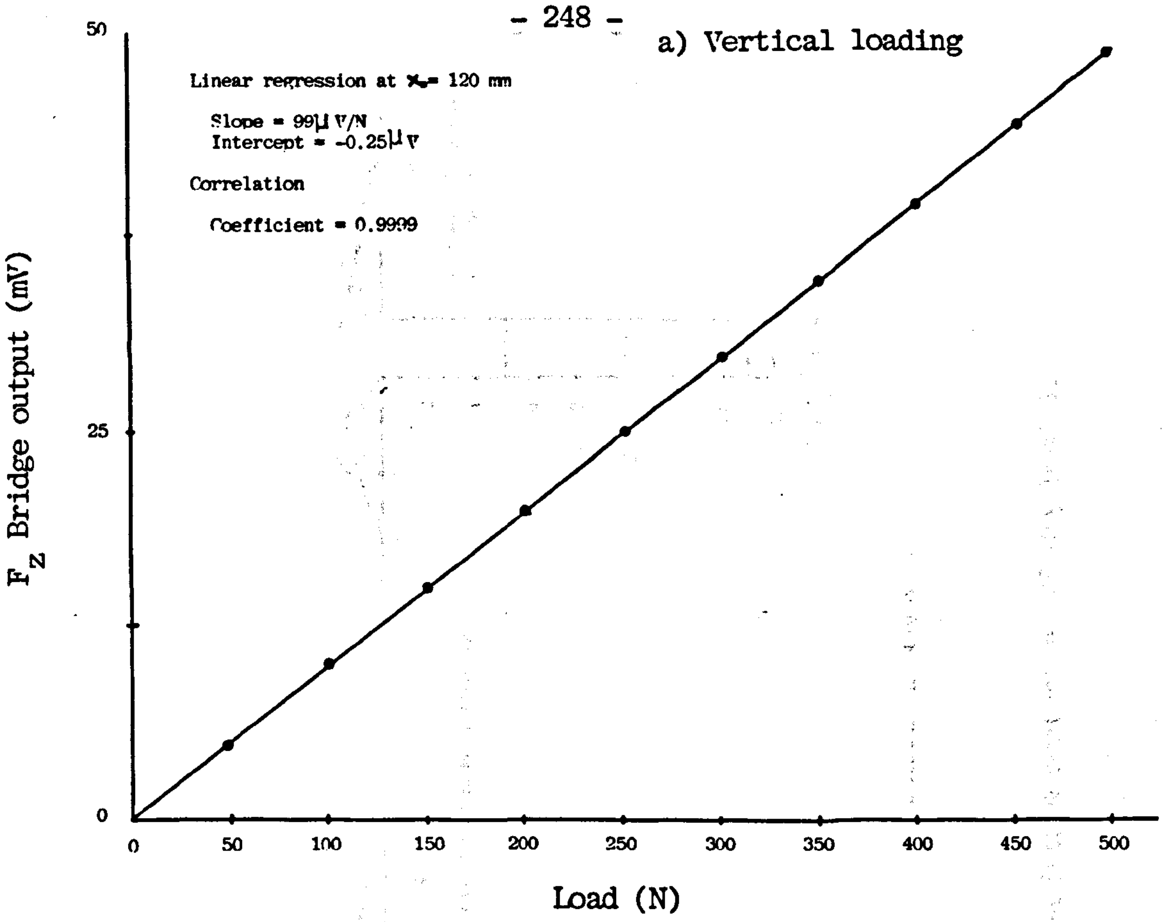


Figure 5.21 Relationship between output voltage and applied load for F_x - Bridge (horizontal loading).



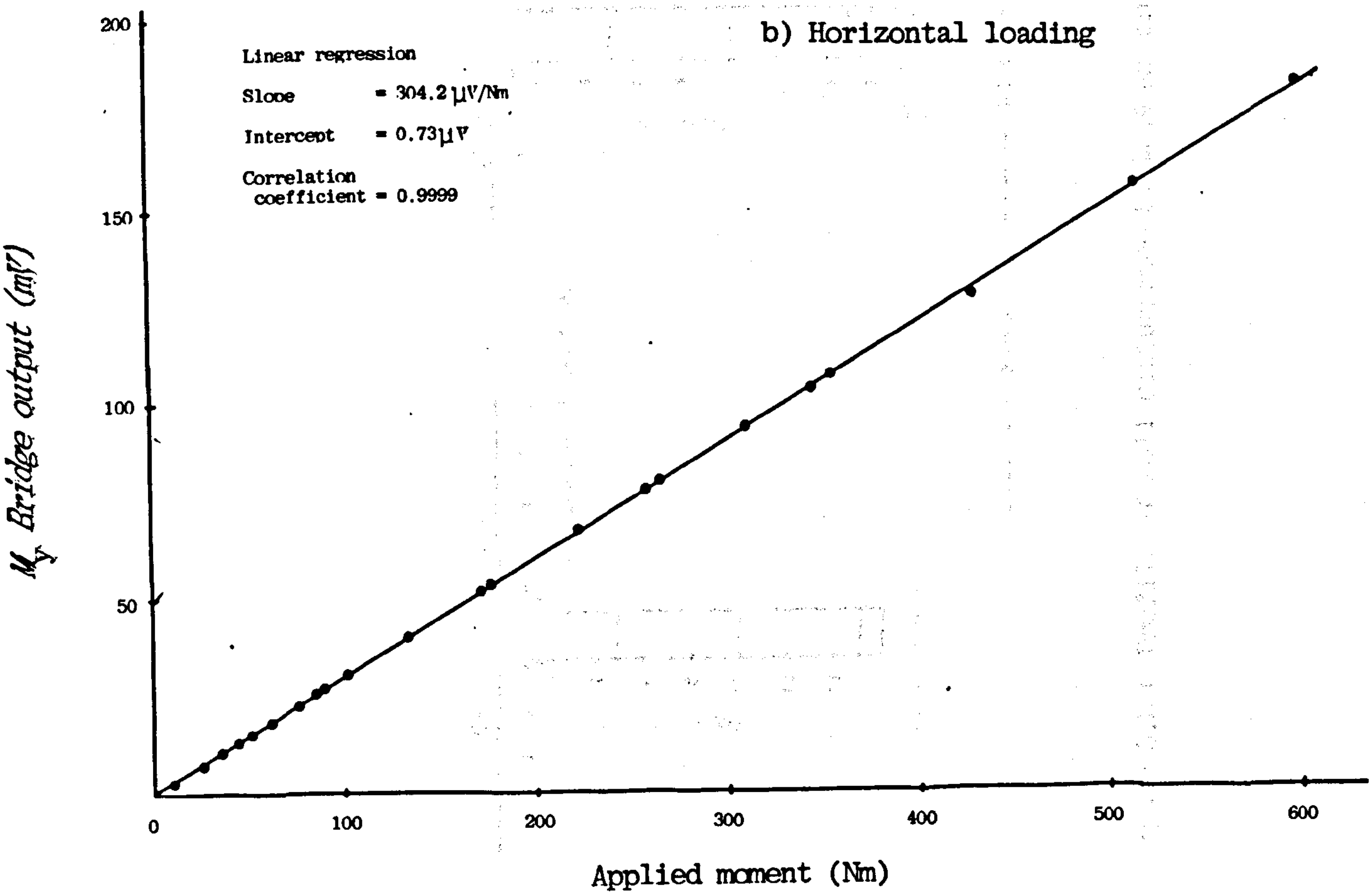


Figure 5.22 F_z and M_y Bridge output voltage.

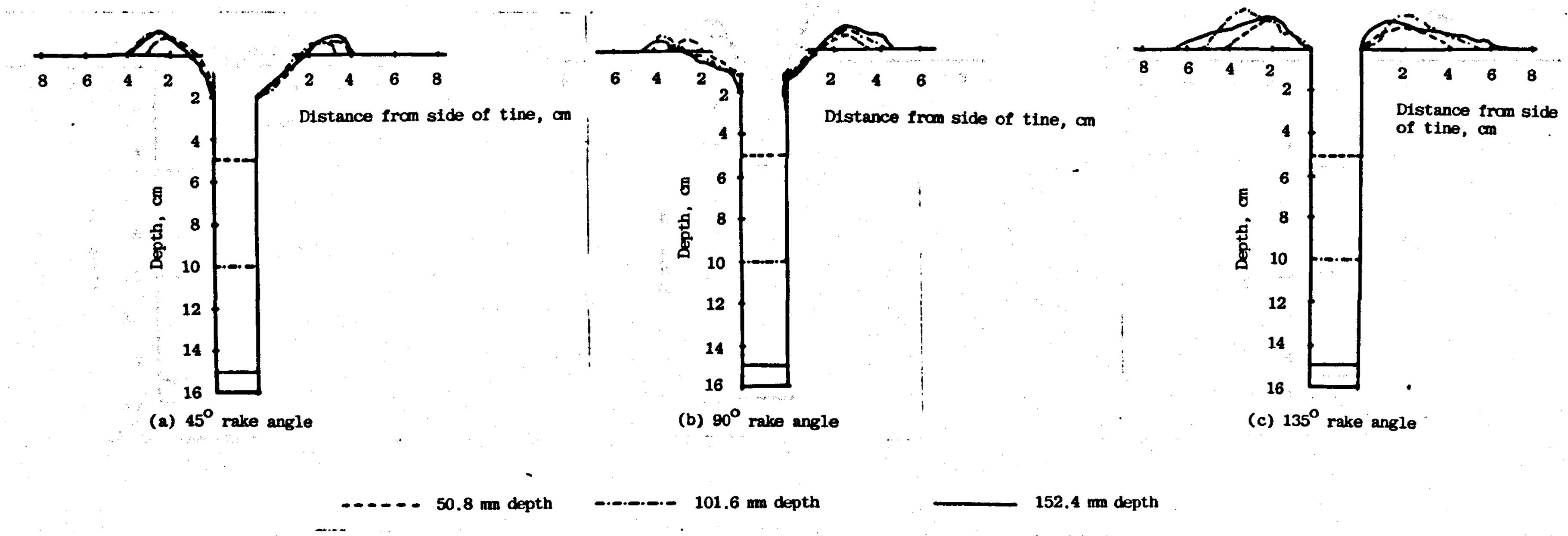


Figure 5.23 Profile of soil disturbance by 25.4 mm tine (moisture content = 42% dry basis).

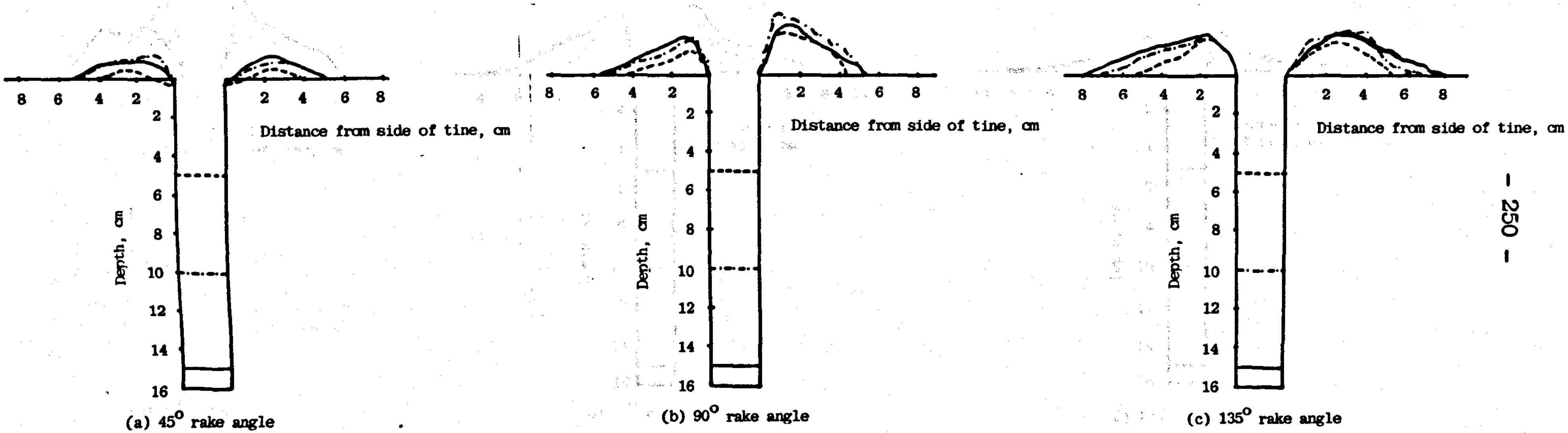


Figure 5.24 Profile of soil disturbance by 25.4 mm tine (moisture content = 56% dry basis).

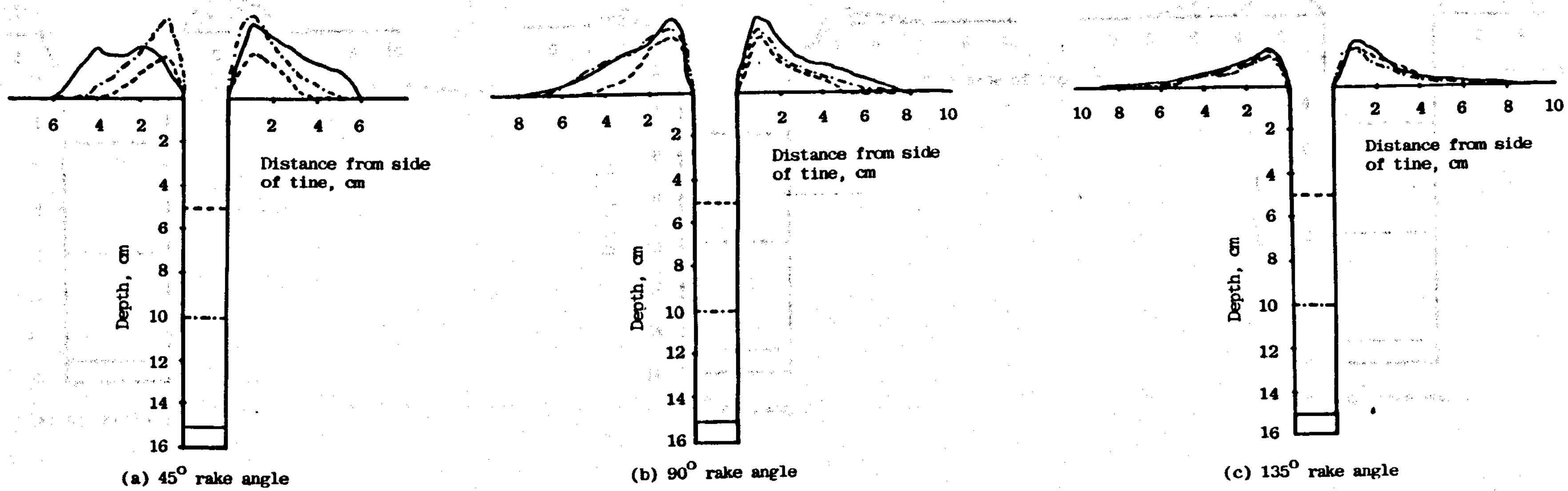


Figure 5.25 Profile of soil disturbance by 25.4 mm tine (moisture content = 70% dry basis).

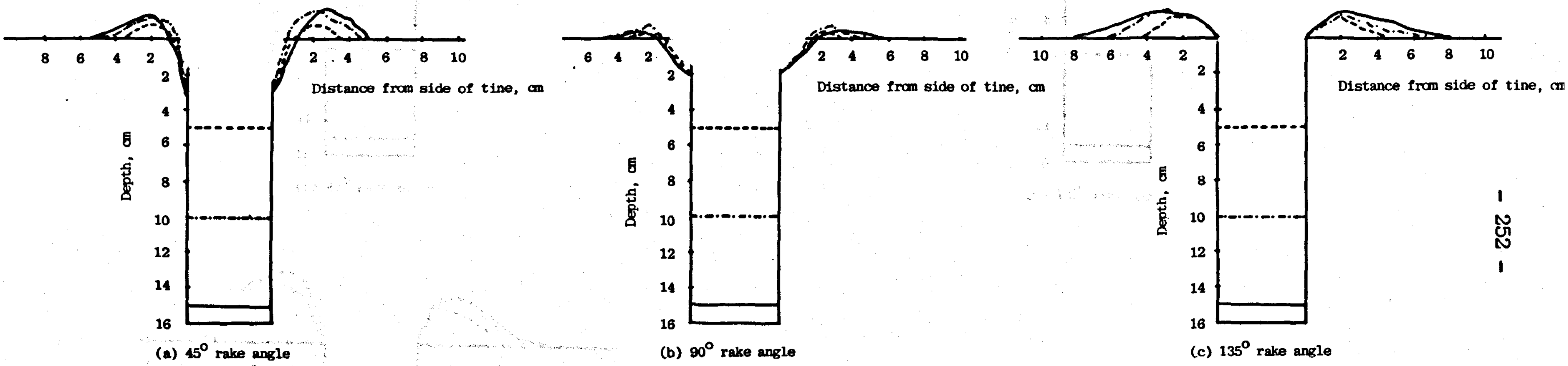
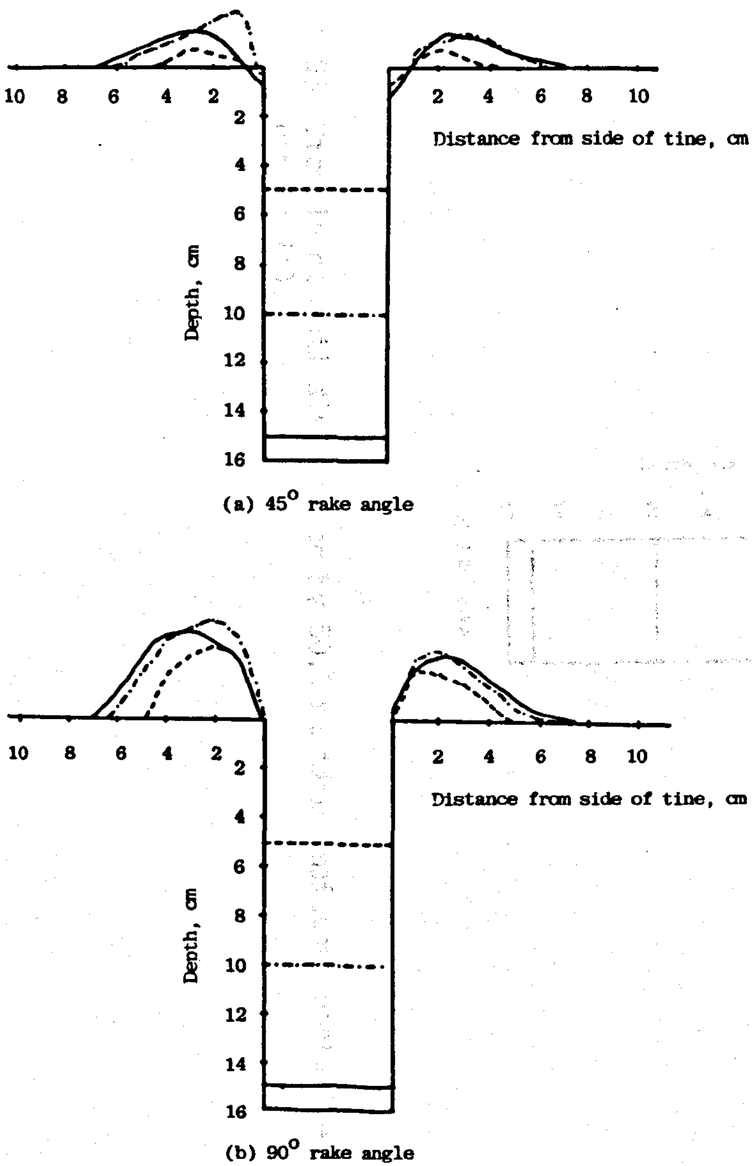


Figure 5.26 Profile of soil disturbance by 50.8 mm tine (moisture content = 42% dry basis).



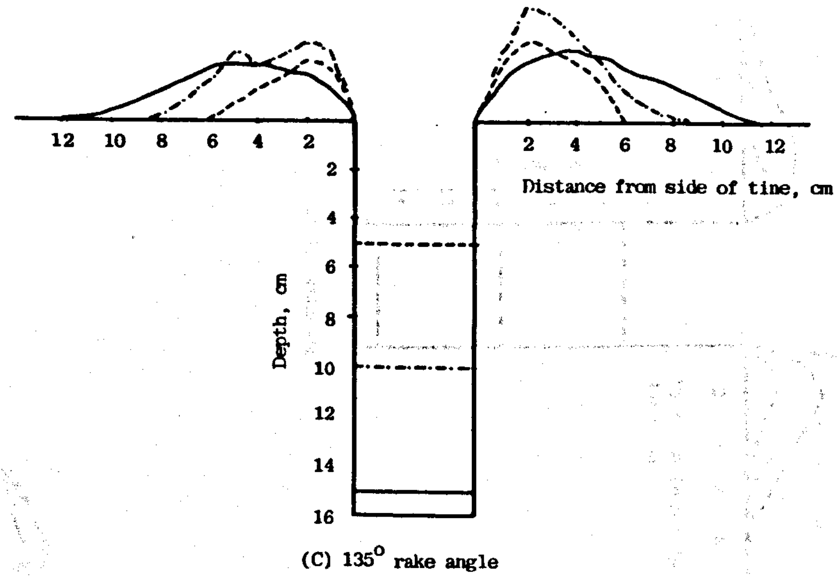


Figure 5.27 Profile of soil disturbance by 50.8 mm tine (moisture content = 56% dry basis).

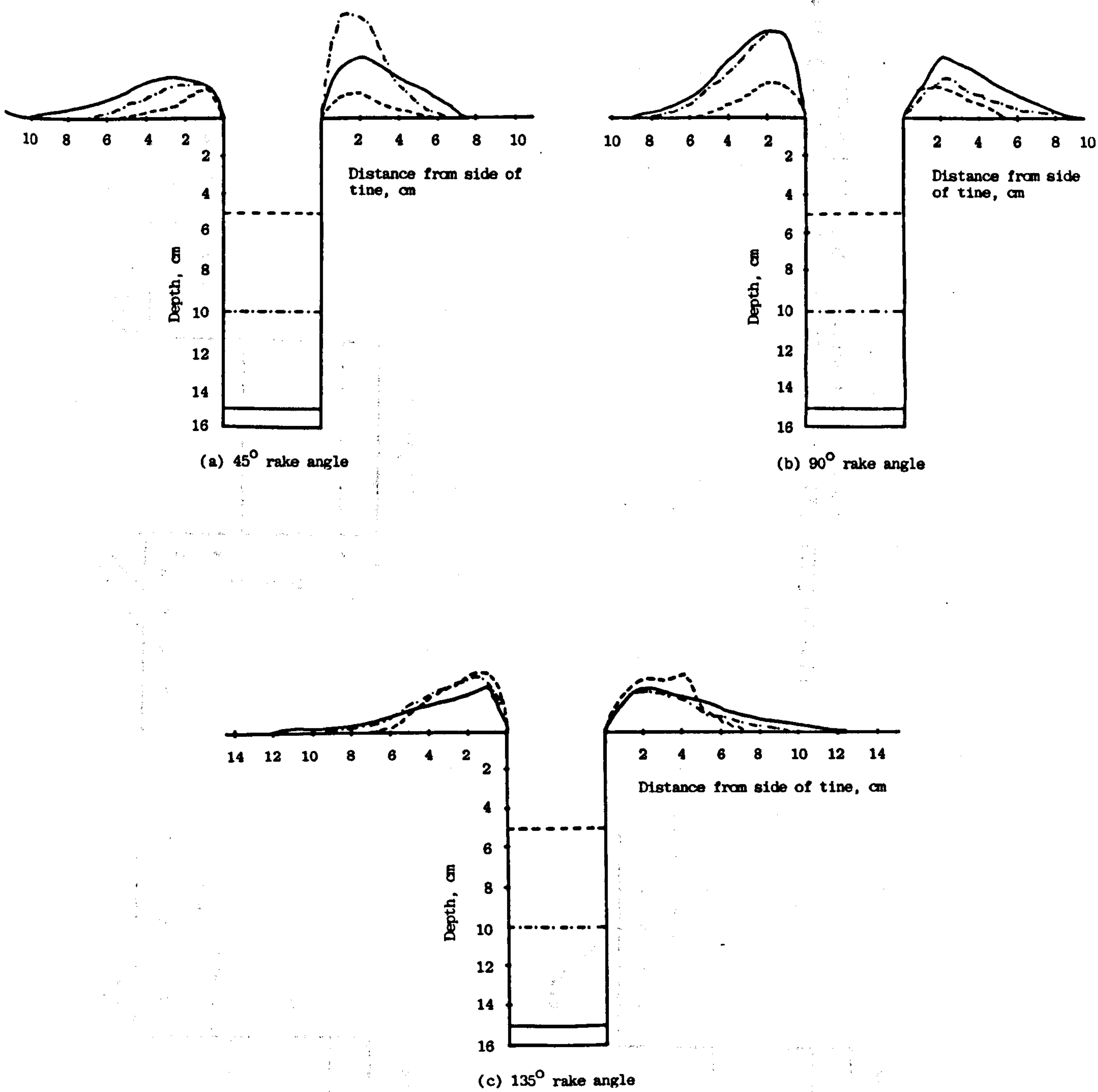


Figure 5.28 Profile of soil disturbance by 50.8 mm tine (moisture content = 70% dry basis).

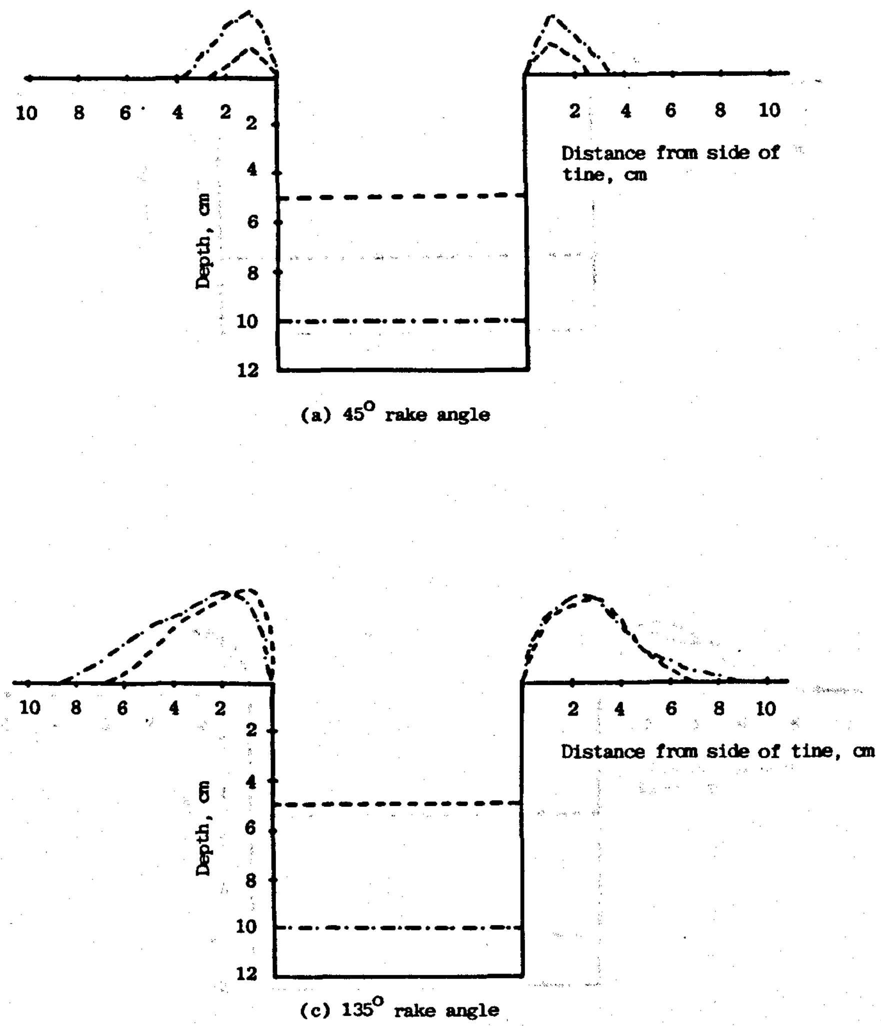


Figure 5.29 Profile of soil disturbance by 101.6 mm tine (moisture content = 70% dry basis).

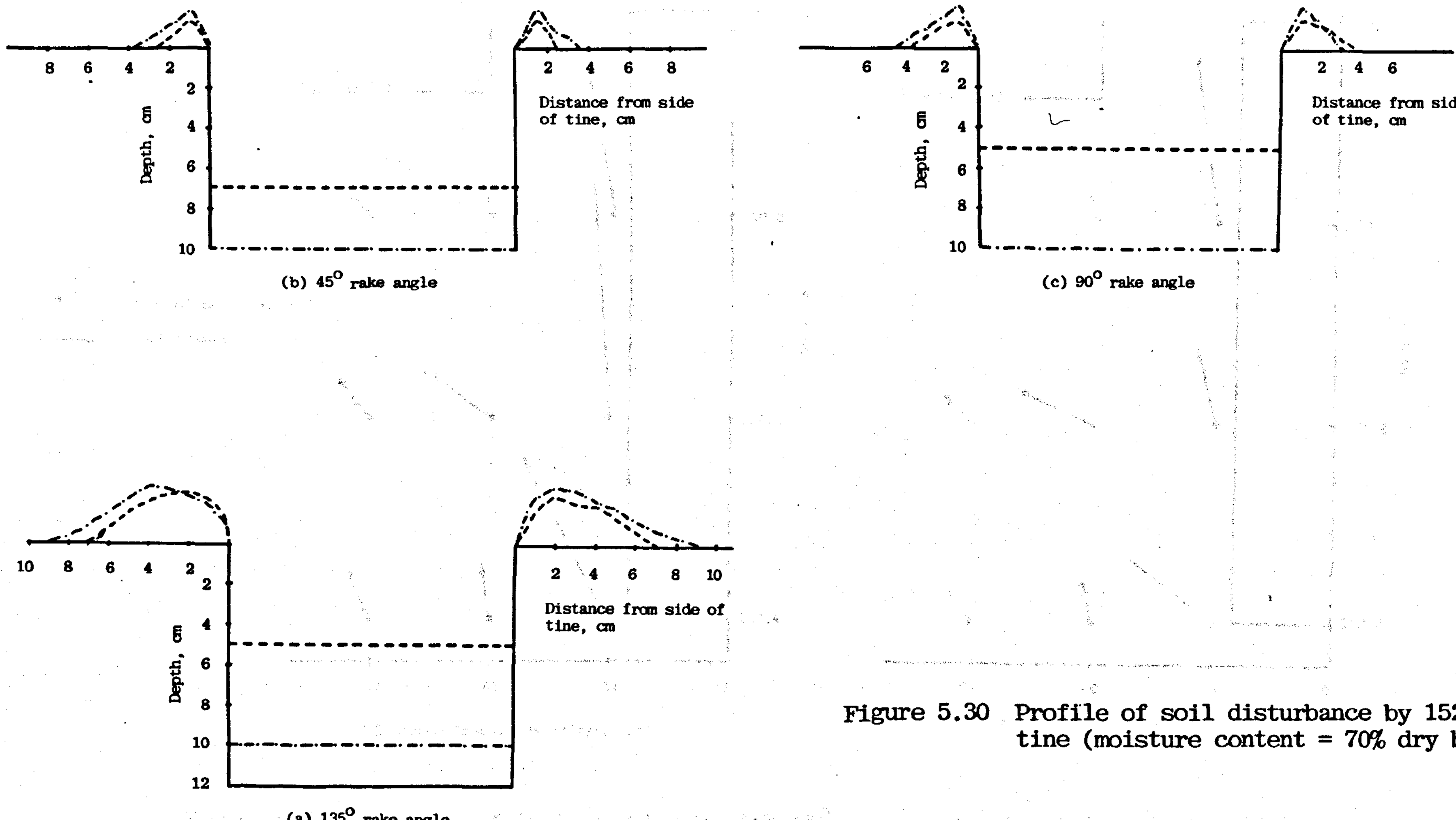


Figure 5.30 Profile of soil disturbance by 152.4 mm tine (moisture content = 70% dry basis).

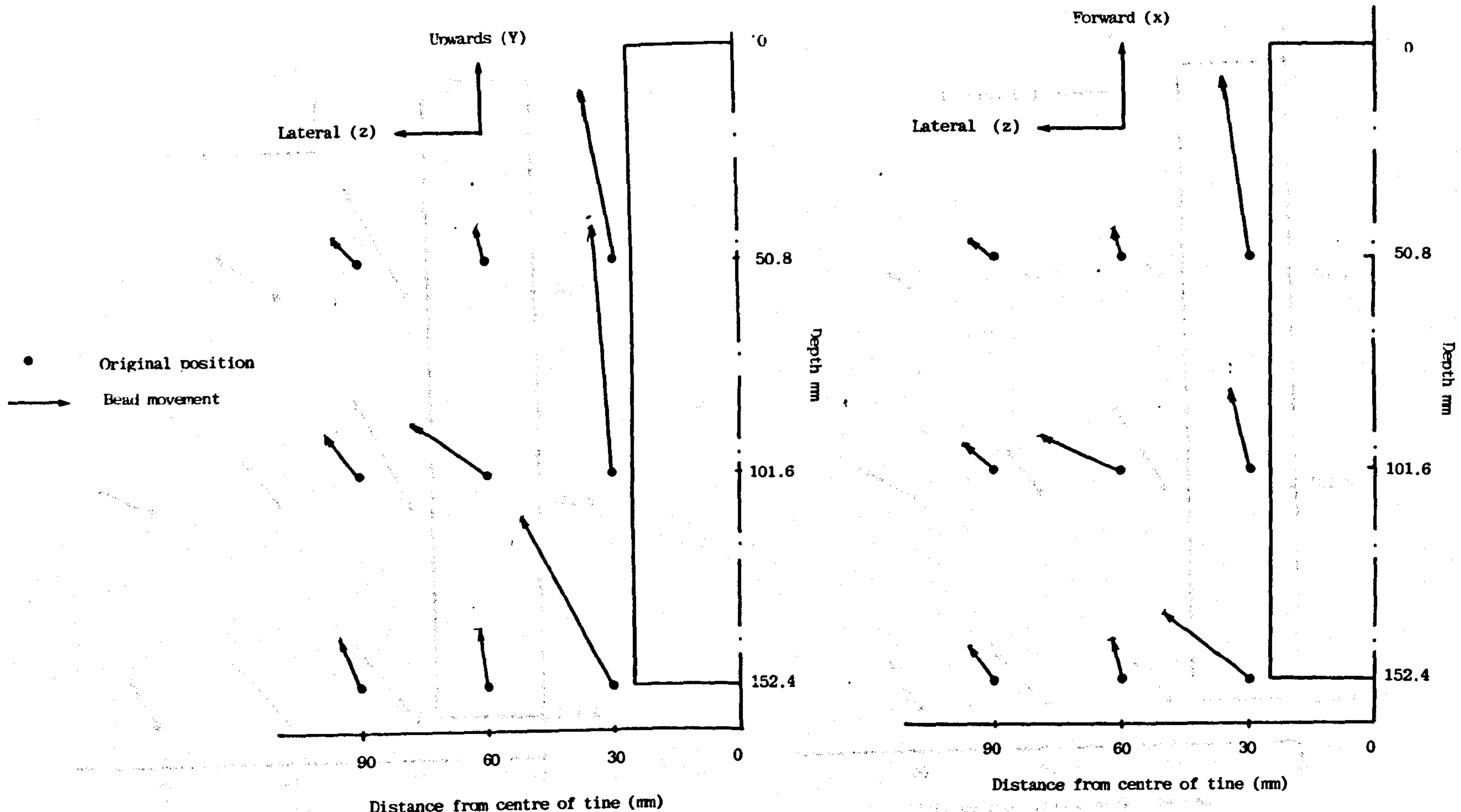


Figure 5.31 Movement of implanted beads with 45° rake angle tine (tine width = 50.8 mm, moisture content = 70% dry basis)

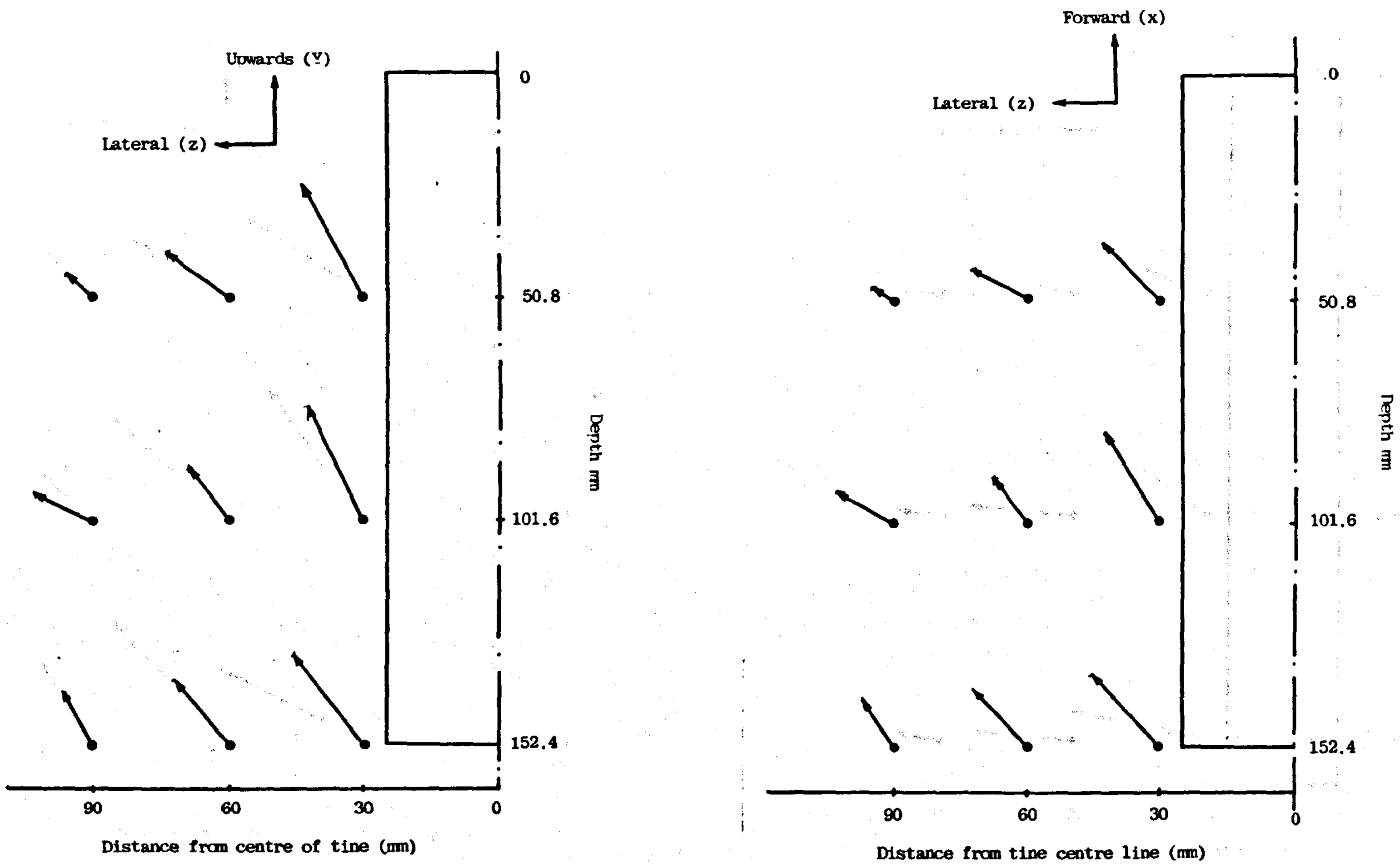


Figure 5.32 Movement of implanted beads with 90° rake angle tine (tine width = 50.8 mm, moisture content = 70% dry basis).

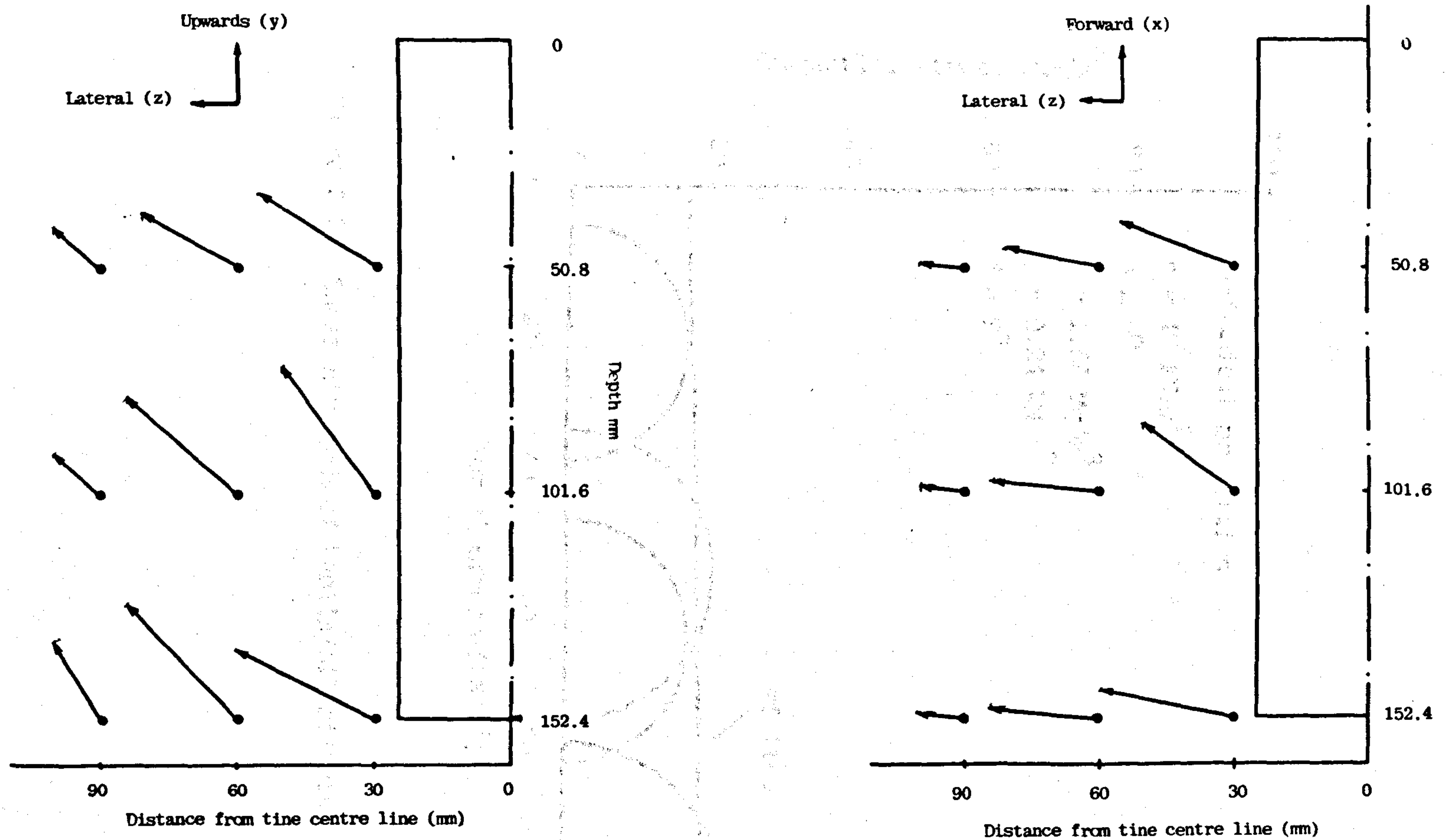


Figure 5.33 Movement of implanted beads with 135^{o} rake angle tine (tine width = 50.8 mm, moisture content = 70% dry basis).

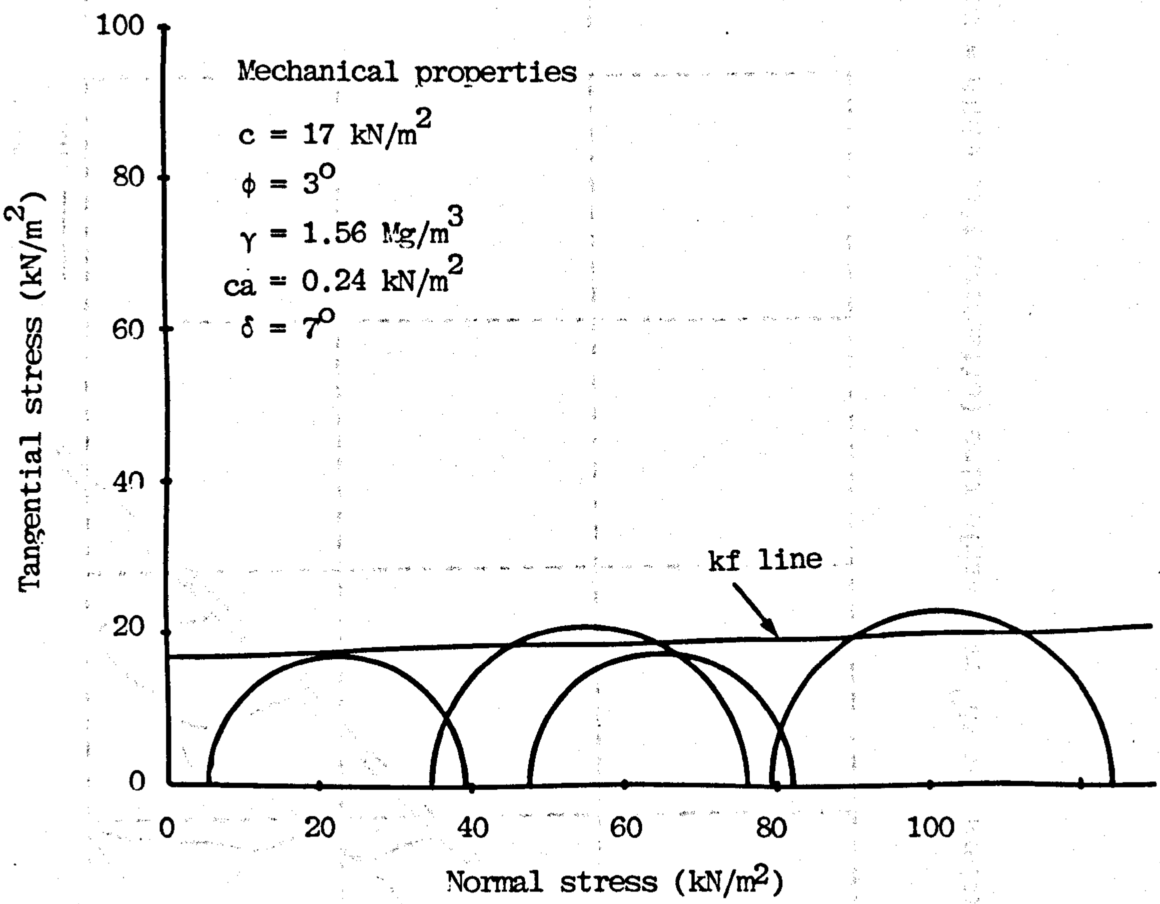


Figure 5.34 Shear strength of kaolin/oil mixture

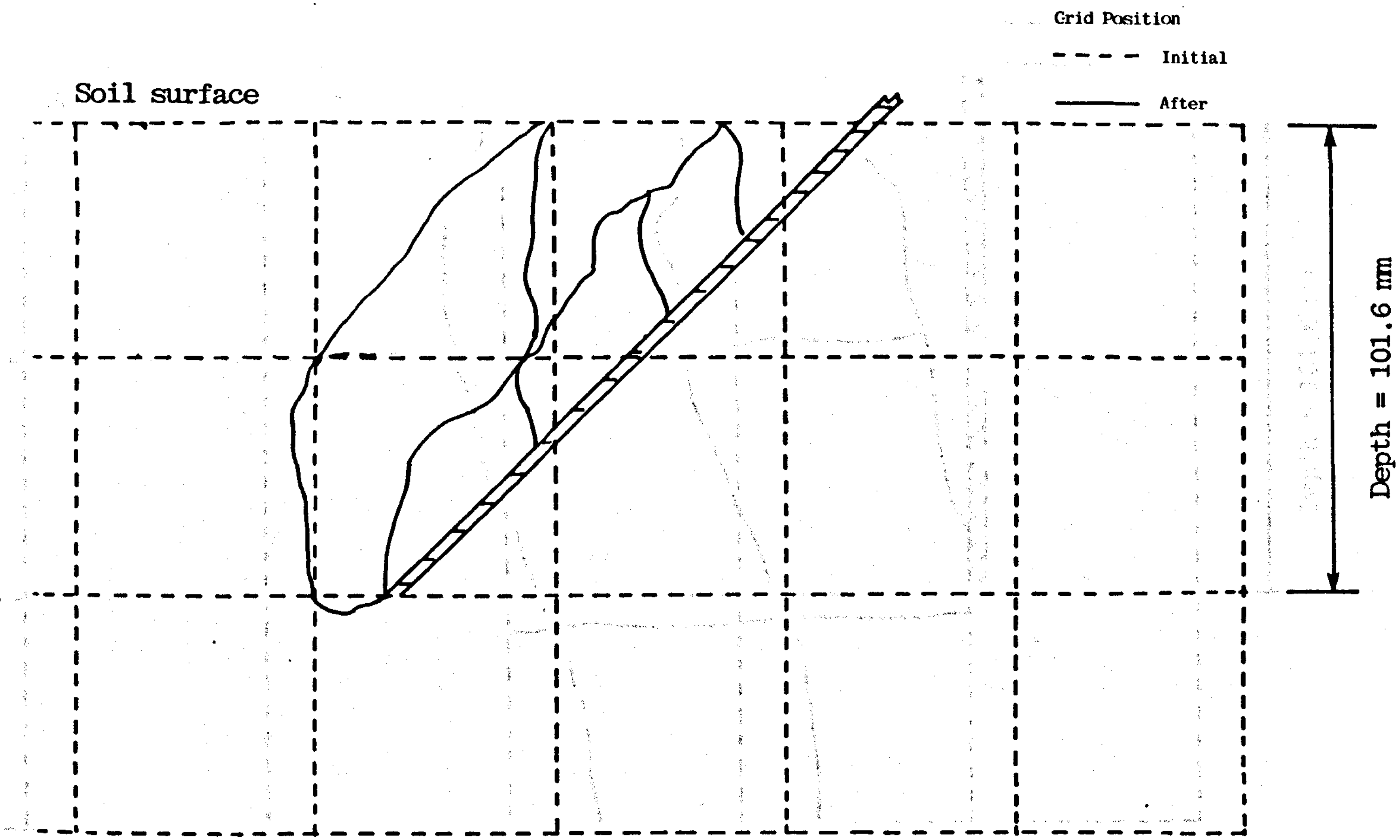


Figure 5.35 Talcum grid pattern for 45^{o} rake angle tine (effective tine width = 25.4 mm).

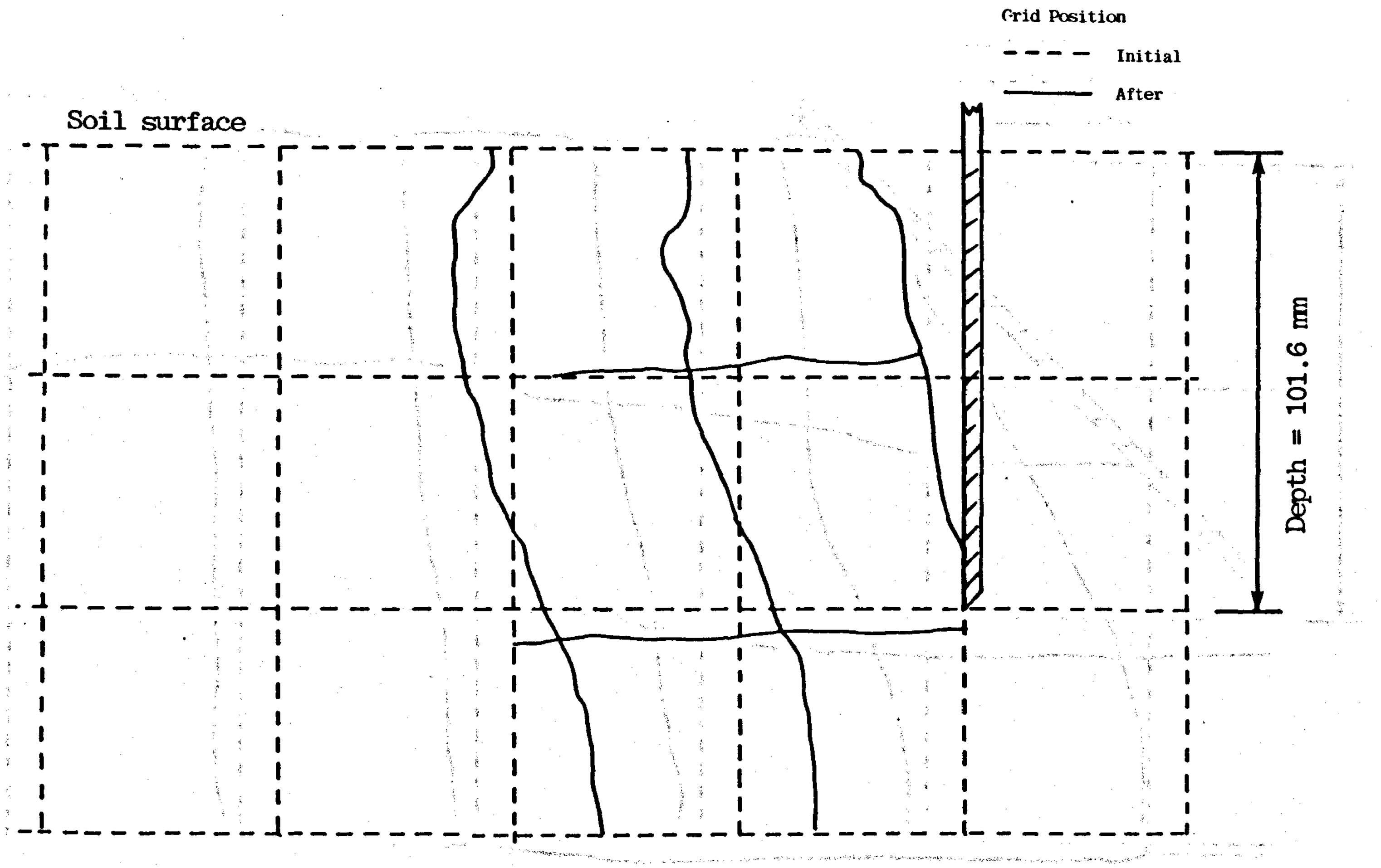


Figure 5.36 Talcum grid pattern for 90° rake angle tine (affective tine width = 25.4 mm).

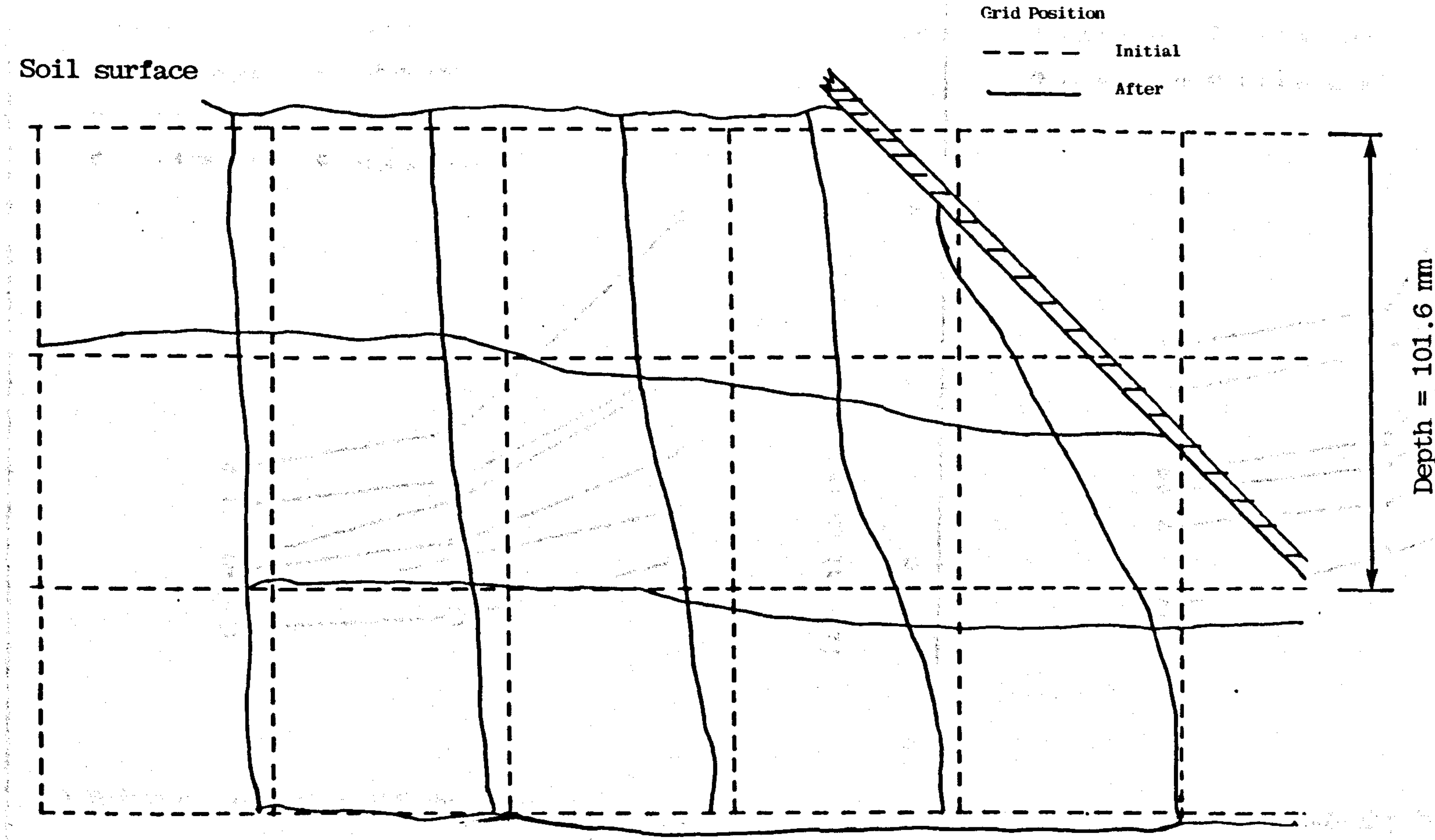


Figure 5.37 Talcum grid pattern for 135° rake angle tine (effective tine width = 25.4 mm).

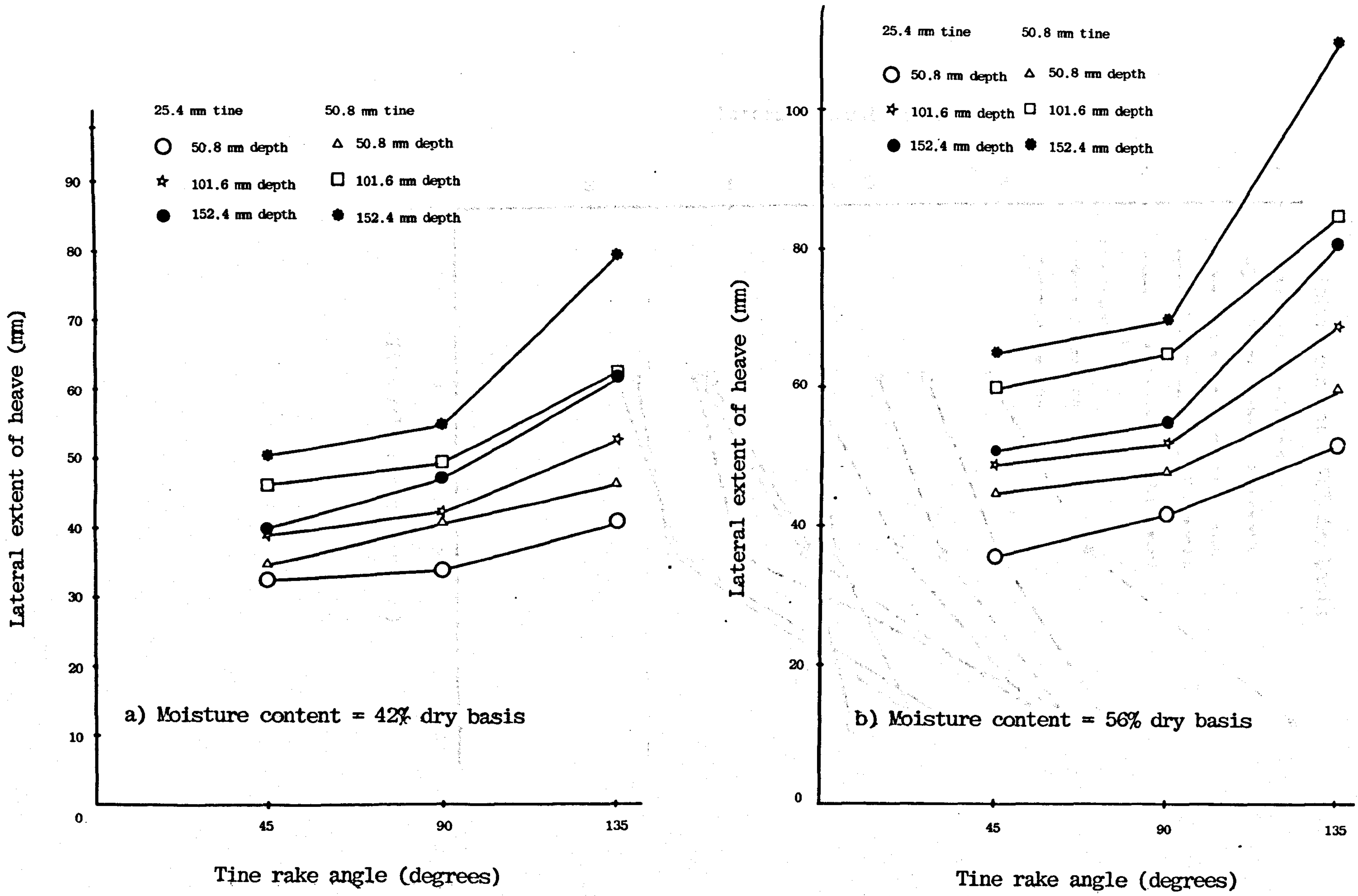
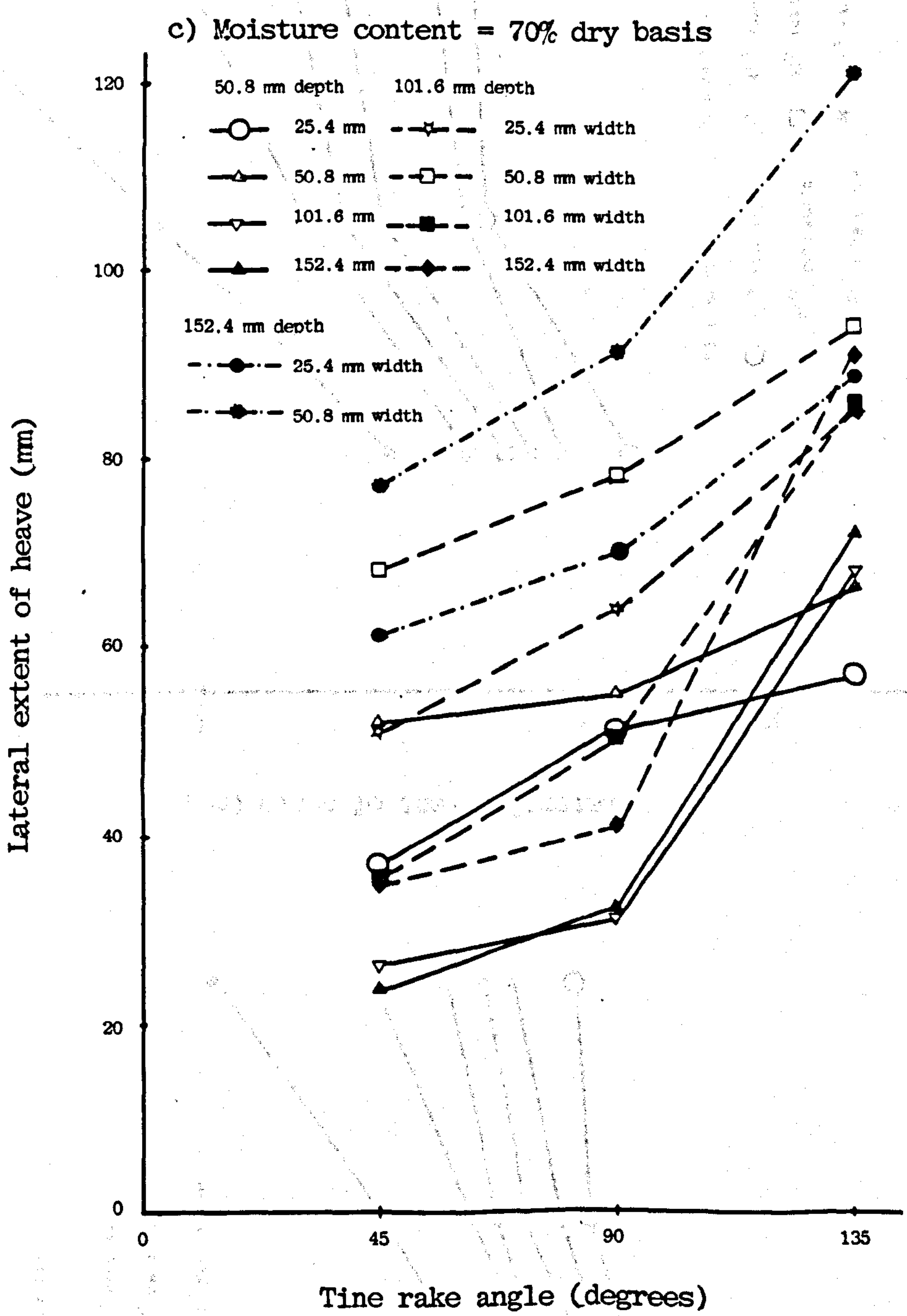


Figure 5.38 Relationship between lateral extent of heave and tine rake angle.


c) Moisture content = 70% dry basis
50.8 mm depth
25.4 mm
50.8 mm
101.6 mm
152.4 mm
101.6 mm depth
25.4 mm width
50.8 mm width
101.6 mm width
152.4 mm width
152.4 mm depth
25.4 mm width
50.8 mm width
Lateral extent of heave (mm)
Tine rake angle (degrees)
0
20
40
60
80
100
120
45
90
135

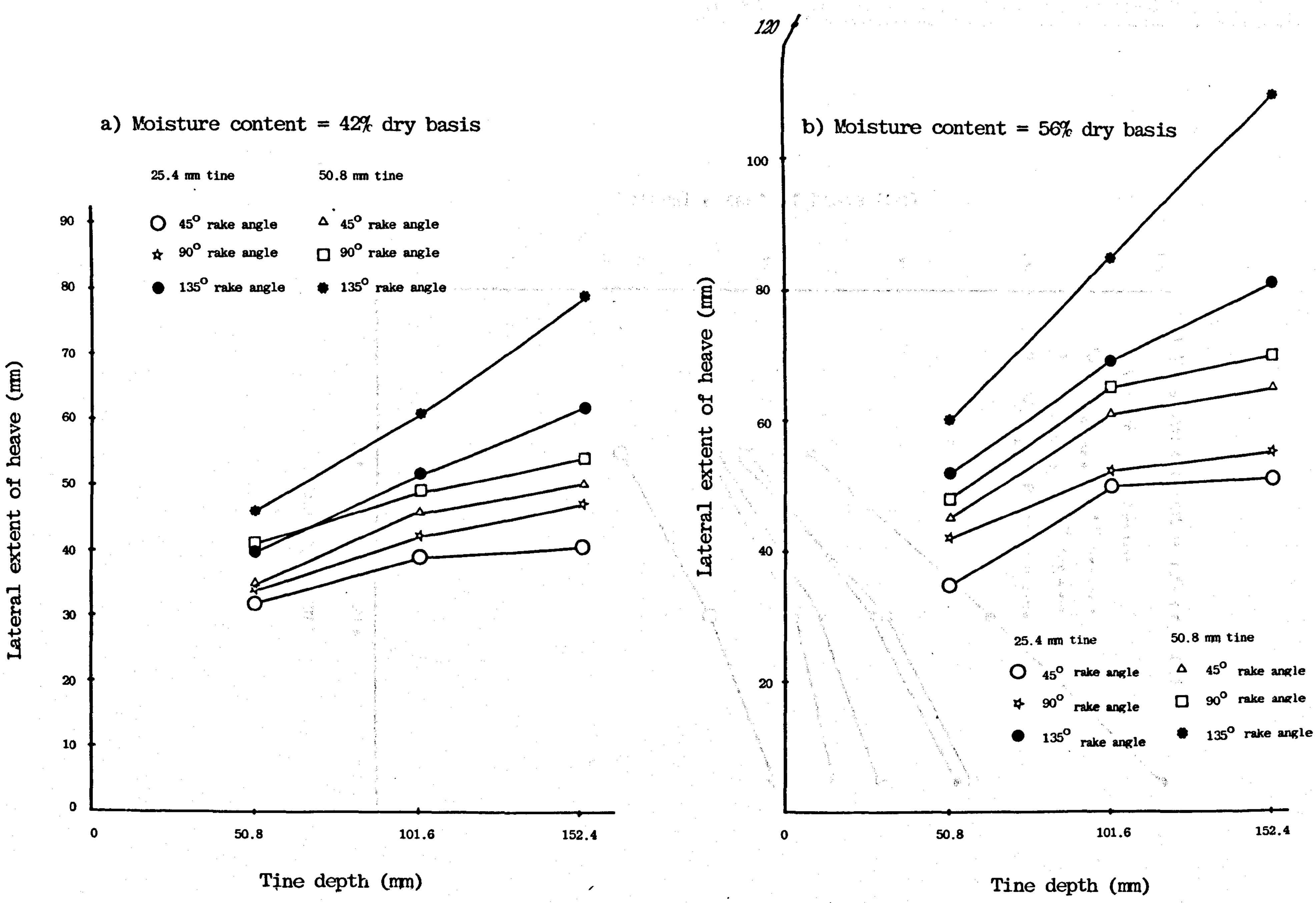
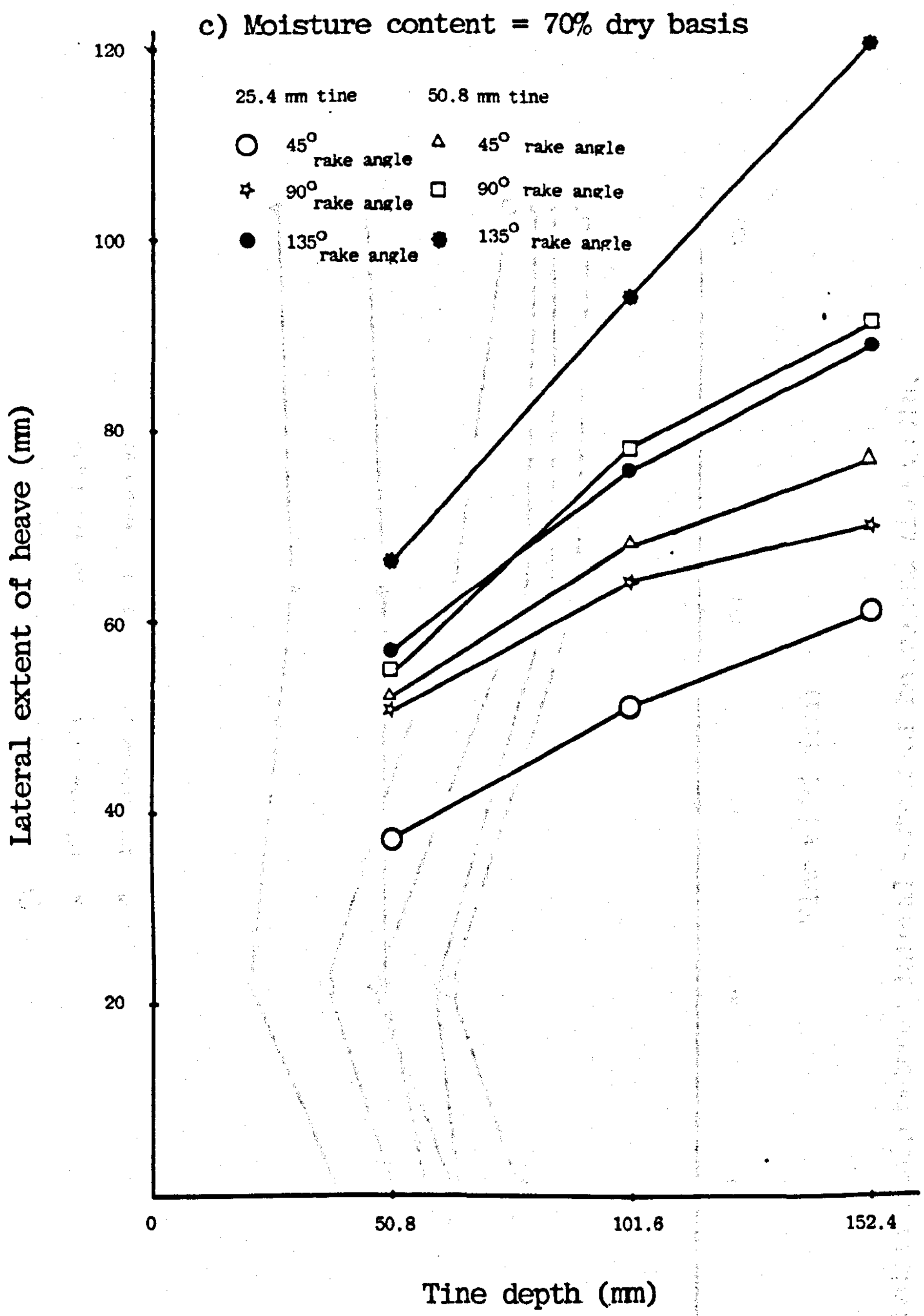


Figure 5.39 Relationship between lateral extent of heave and tine depth.



c) Moisture content = 70% dry basis
25.4 mm tine
50.8 mm tine
45° rake angle
90° rake angle
135° rake angle
45° rake angle
90° rake angle
135° rake angle
120
100
80
60
40
20
0
50.8
101.6
152.4
Lateral extent of heave (mm)
Tine depth (mm)

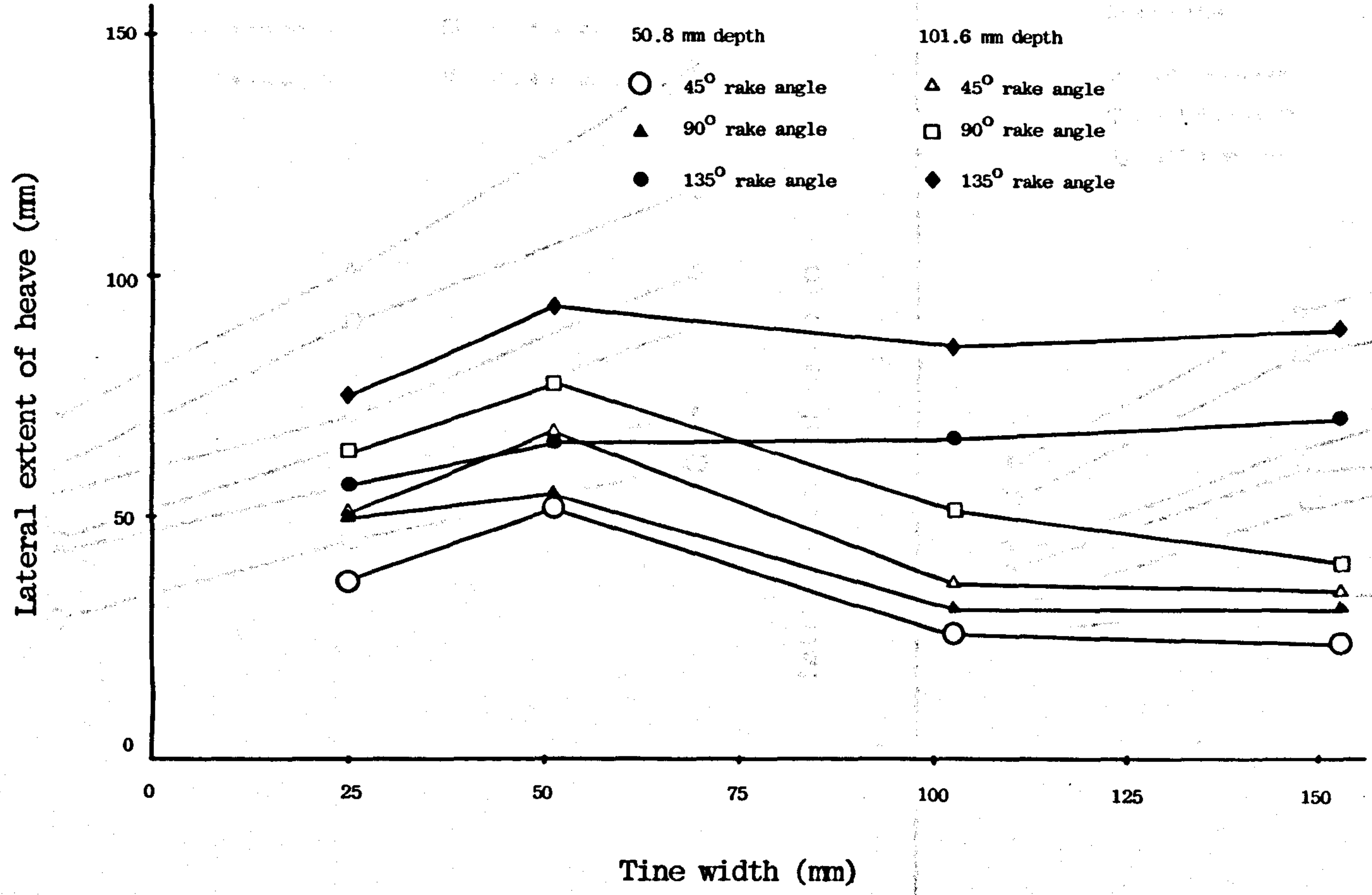


Figure 5.40 Relationship between lateral extent of heave and tine width.

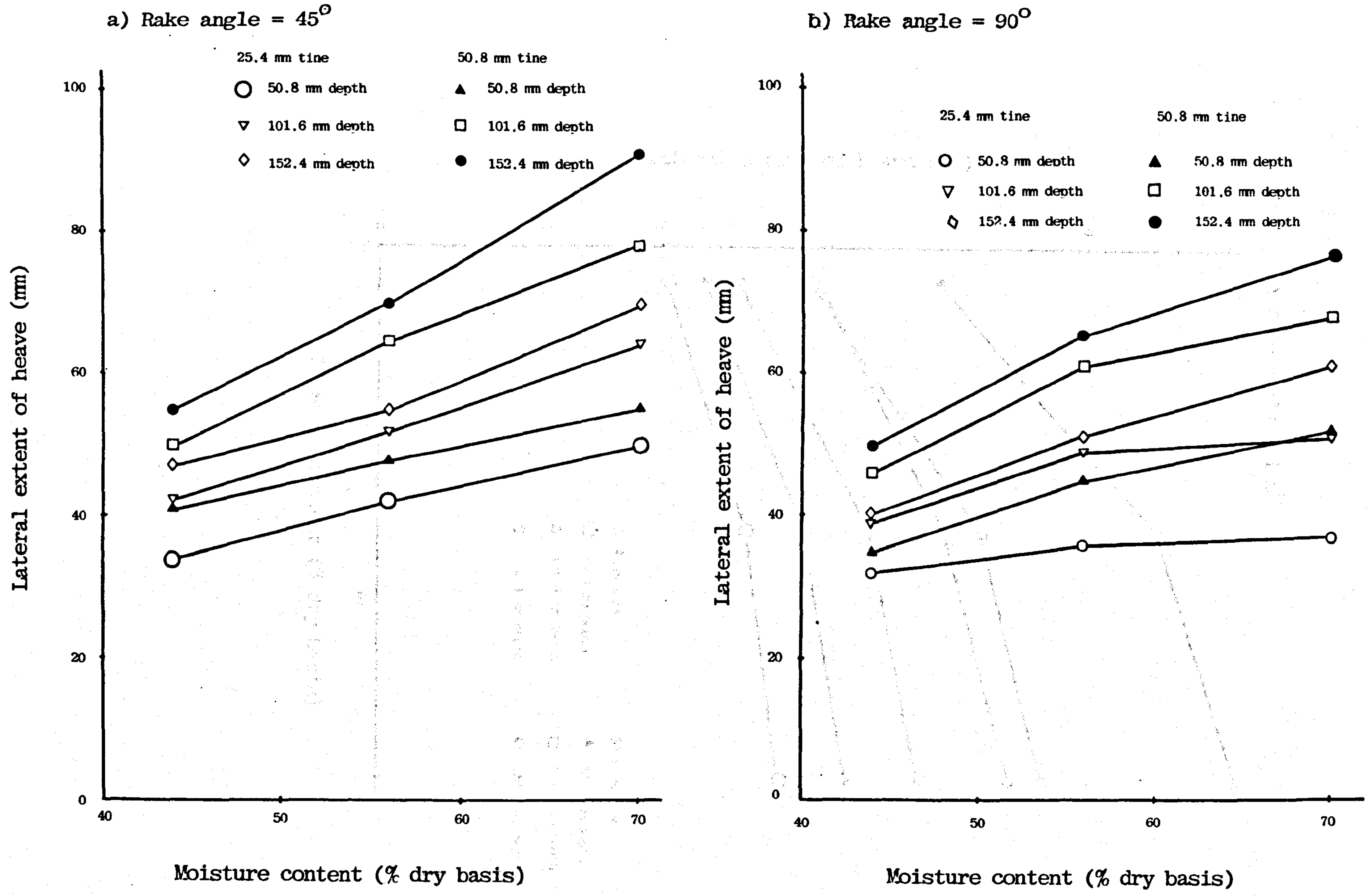
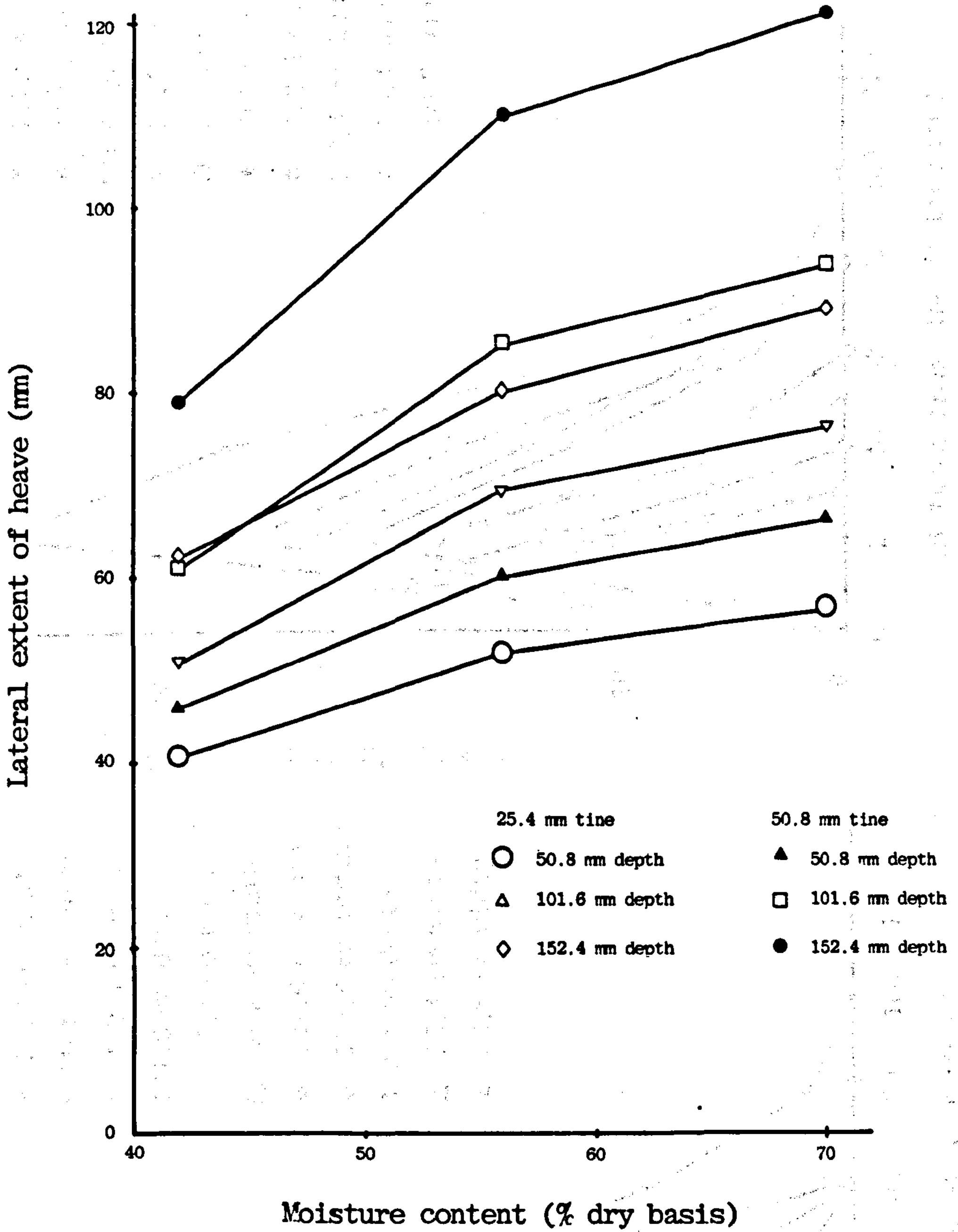


Figure 5.41 Relationship between lateral extent of heave and moisture content.

c) Rake angle = 135^{o}



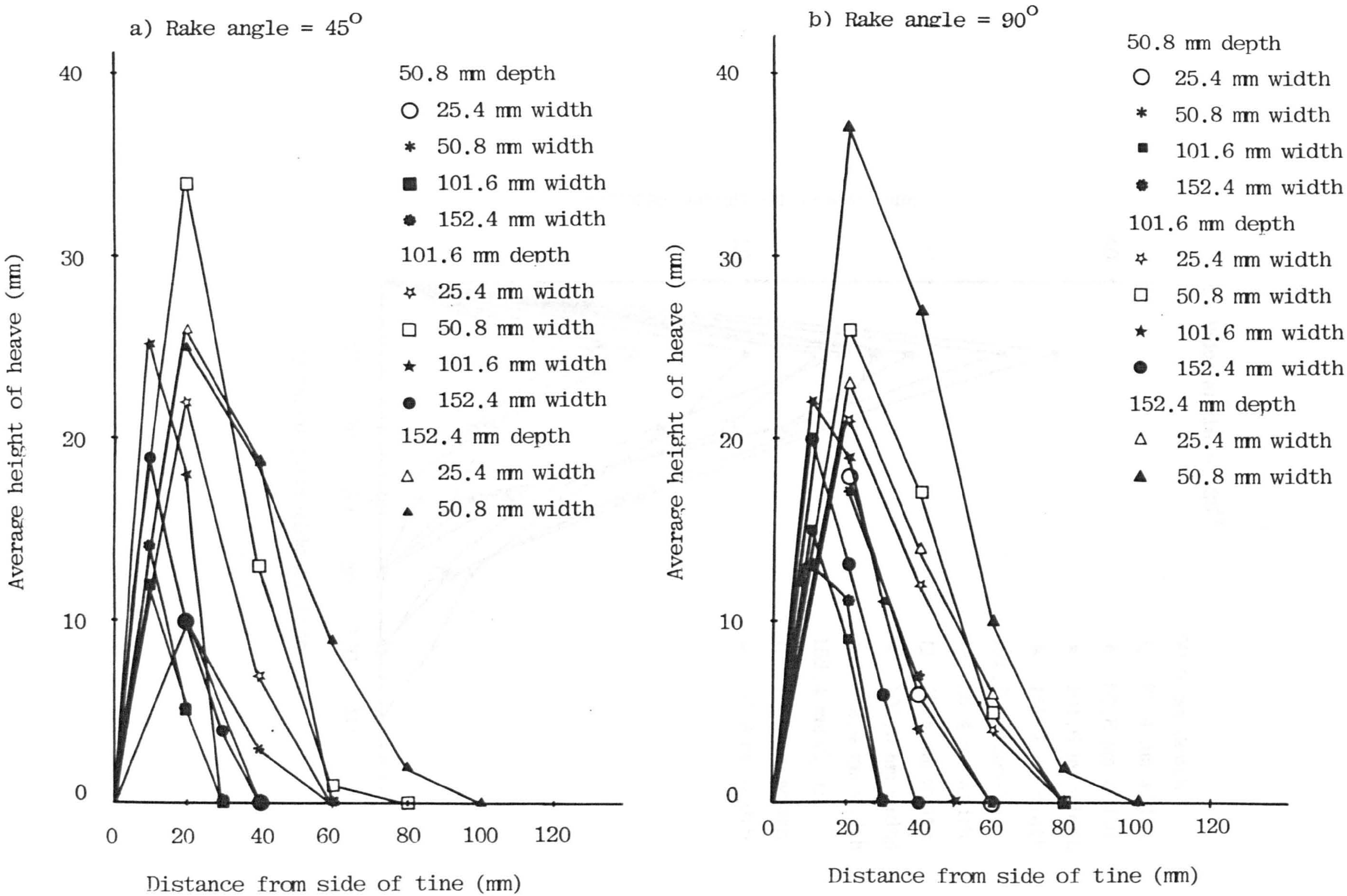
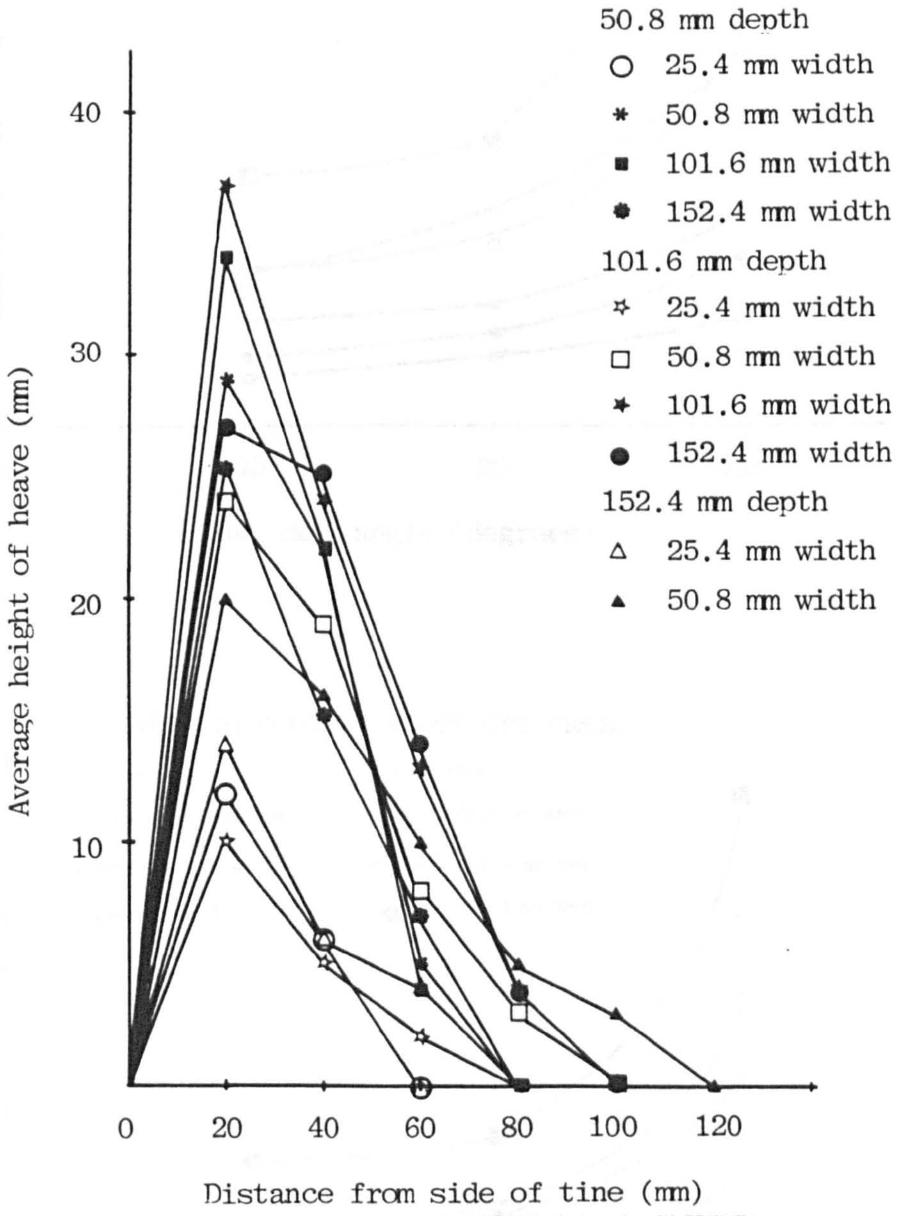


Figure 5.42 Relation of height of heave with distance from side of tine.

c) Rake angle = 135°



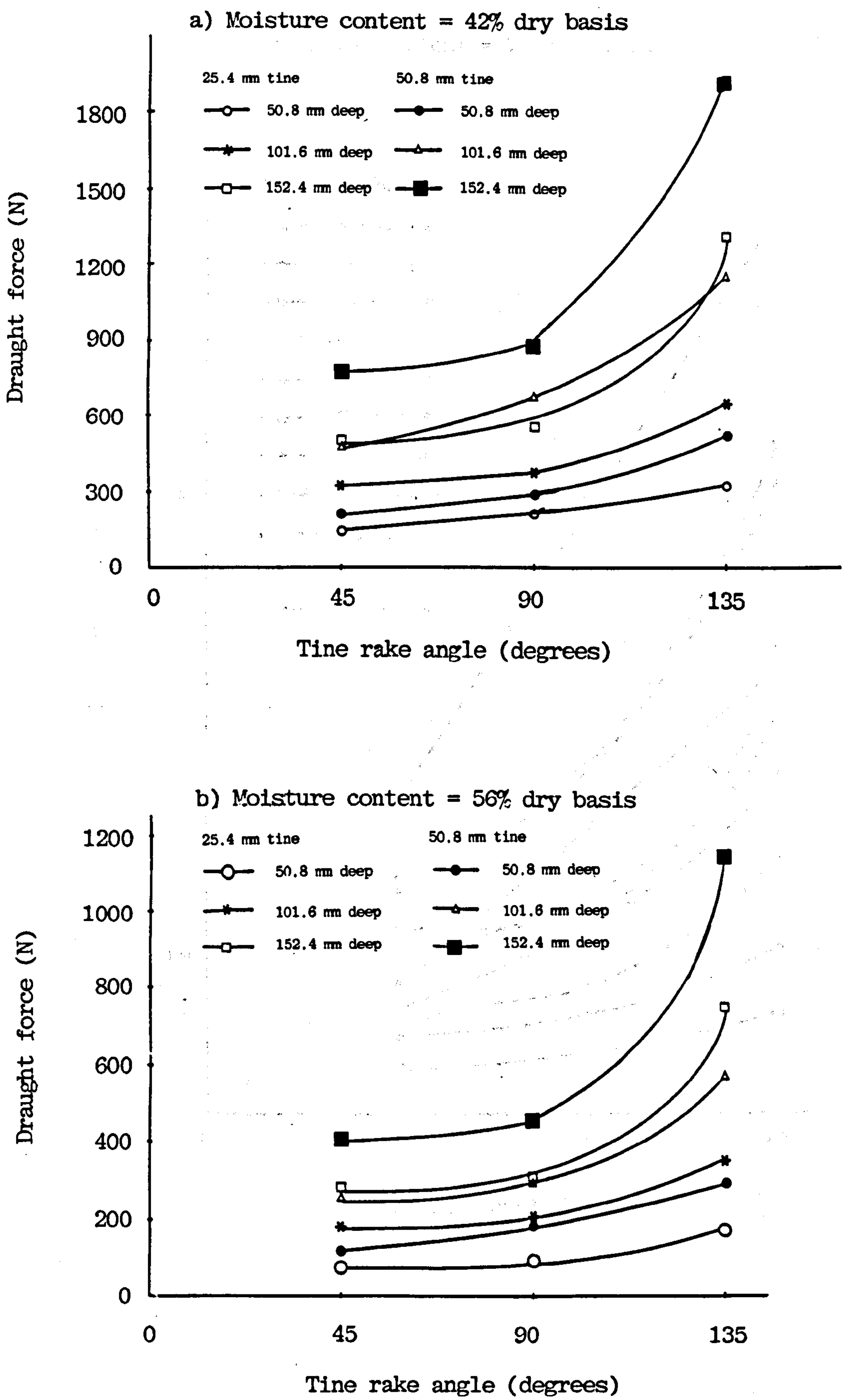
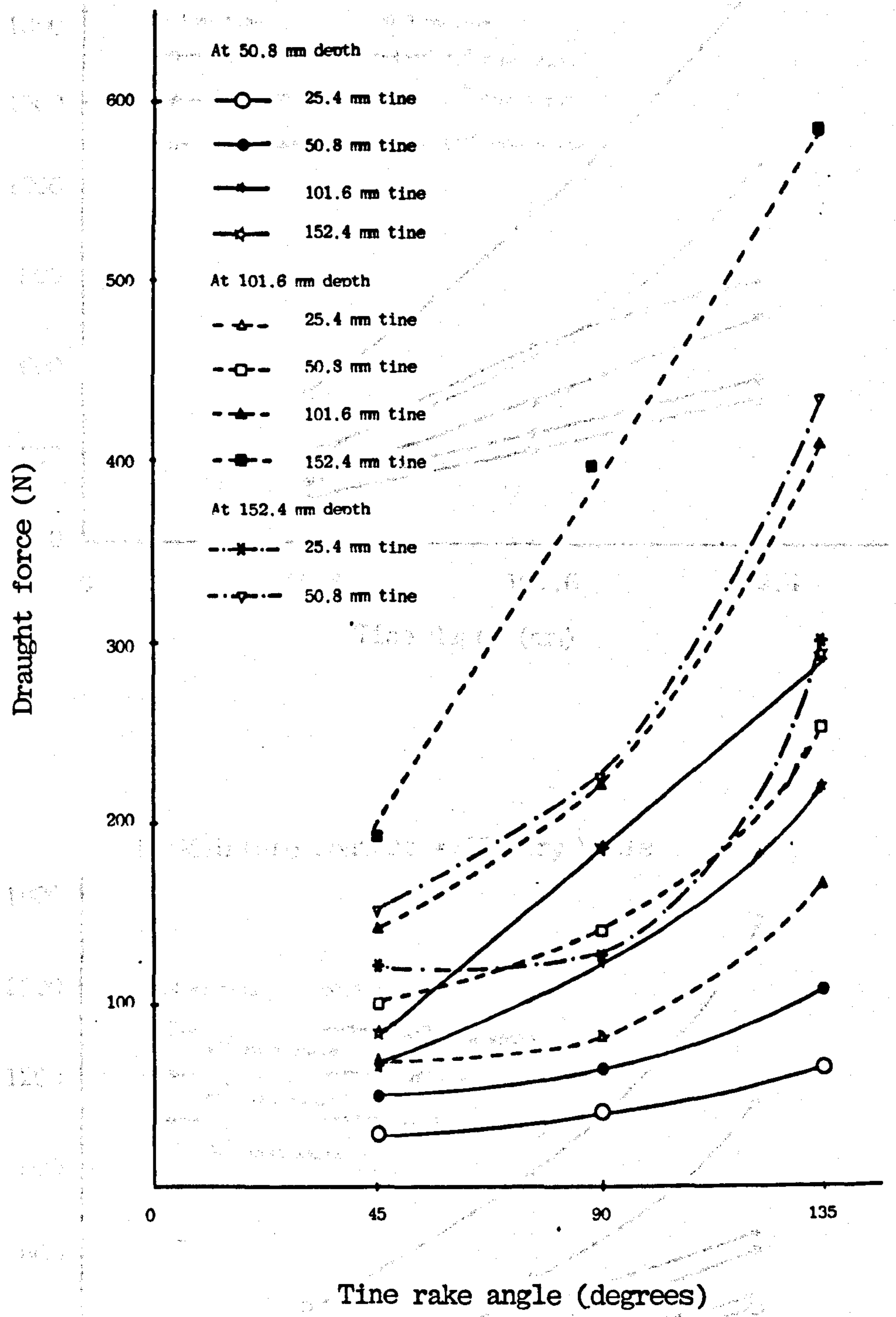
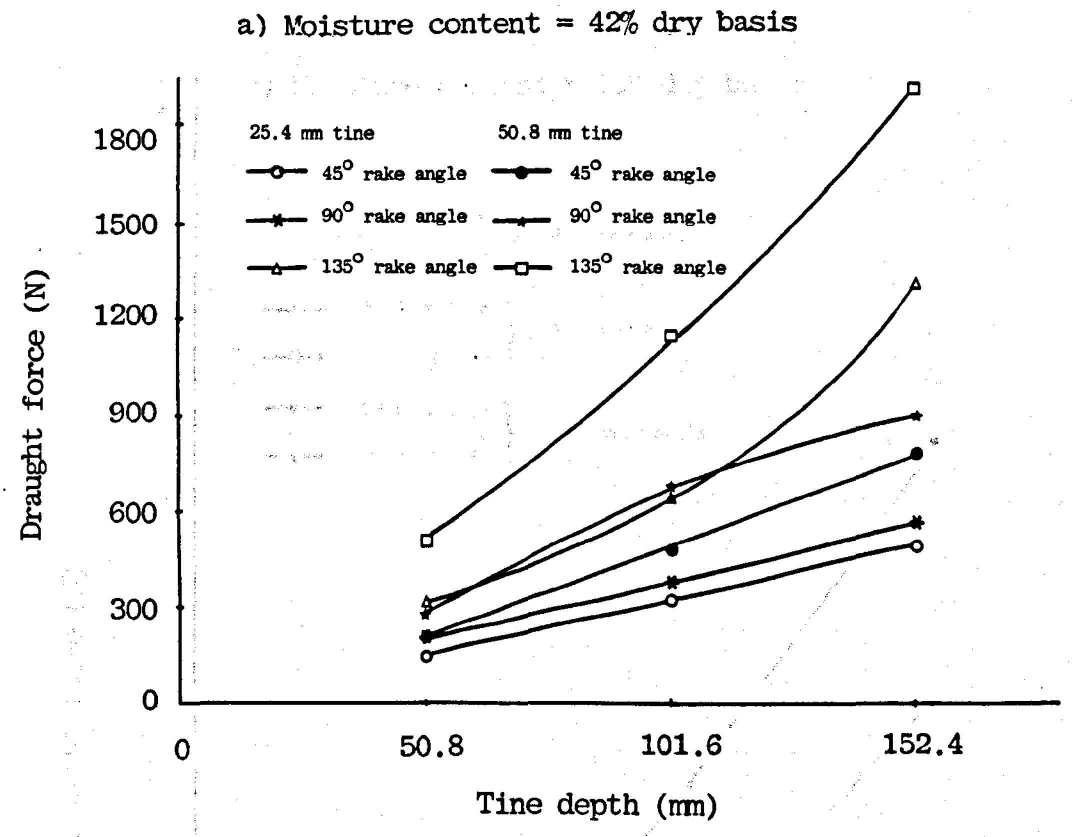


Figure 5.43 Relationship between draught force and tine rake angle.

c) Moisture content = 70% dry basis





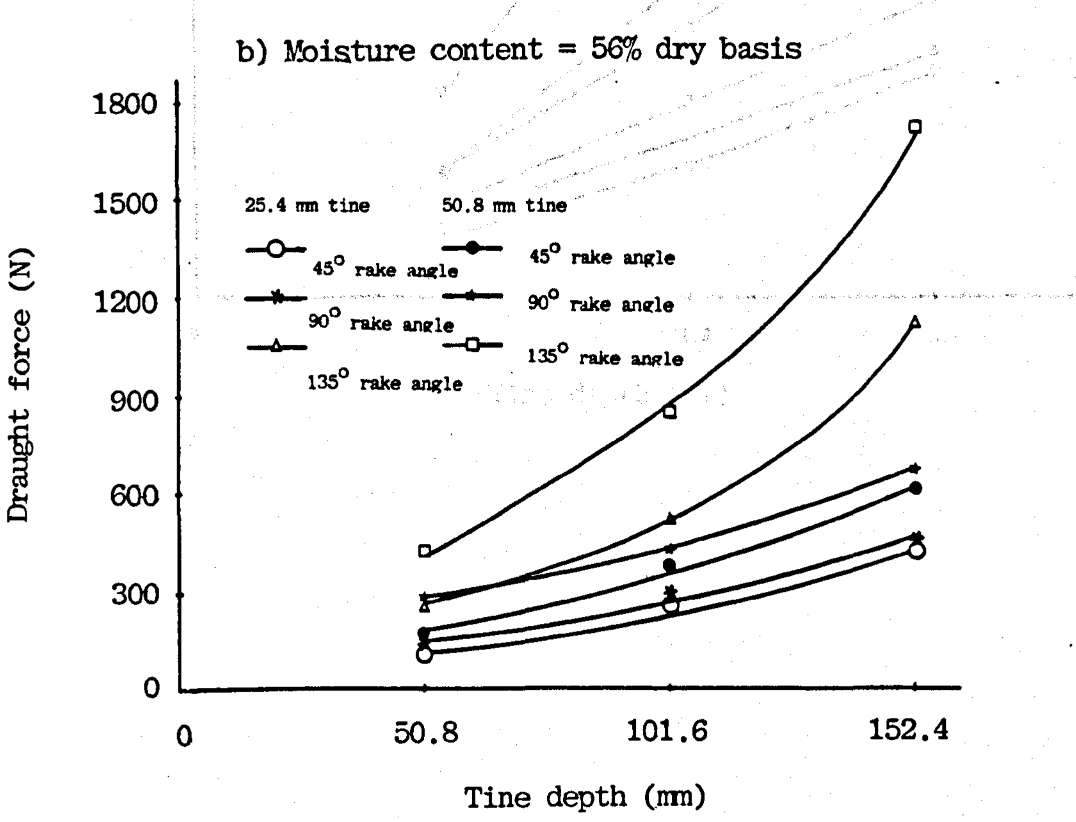
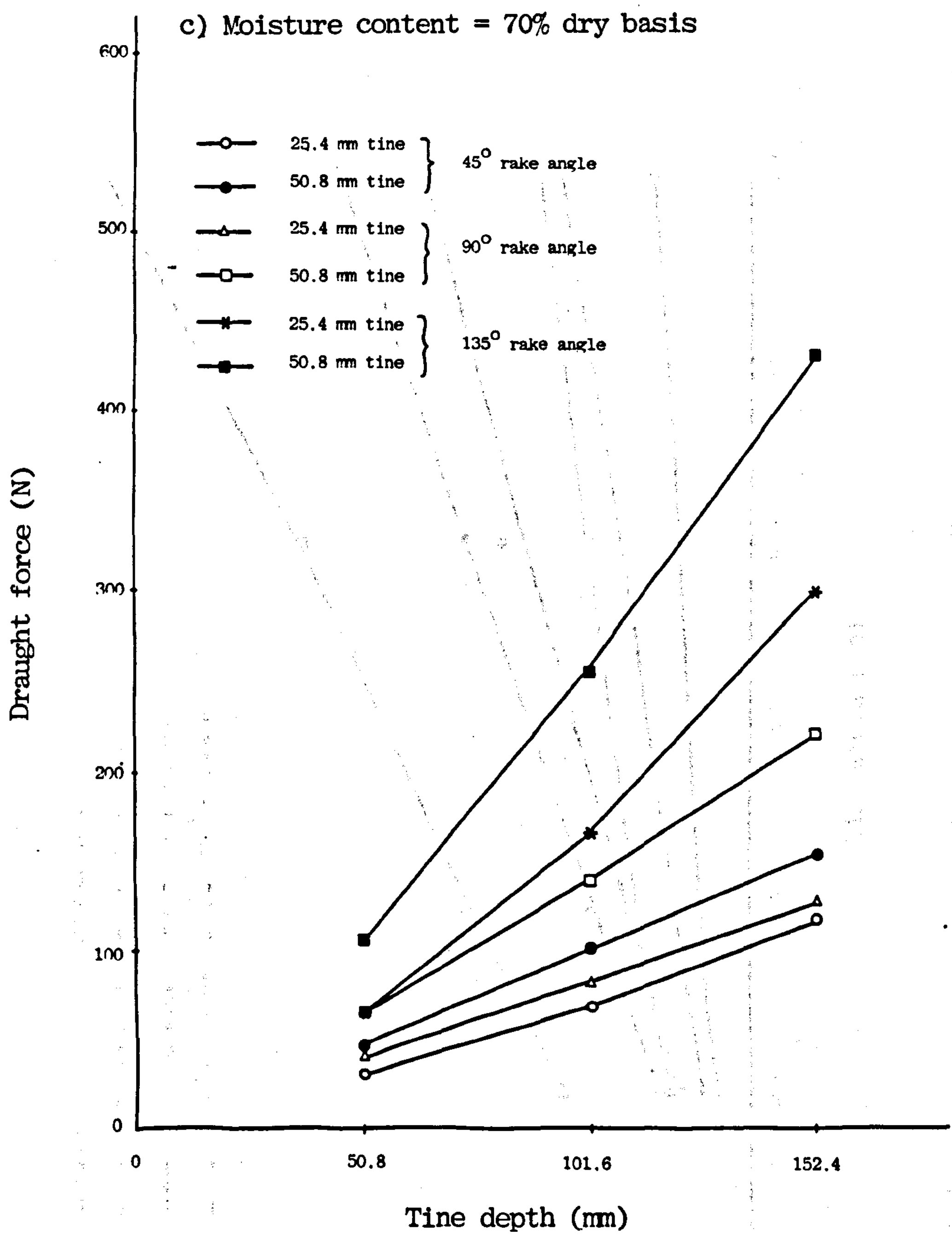


Figure 5.44 Relationship between draught force and tine depth.


c) Moisture content = 70% dry basis
25.4 mm tine
50.8 mm tine
45° rake angle
25.4 mm tine
50.8 mm tine
90° rake angle
25.4 mm tine
50.8 mm tine
135° rake angle
Draught force (N)
600
500
400
300
200
100
0
0
50.8
101.6
152.4
Tine depth (mm)

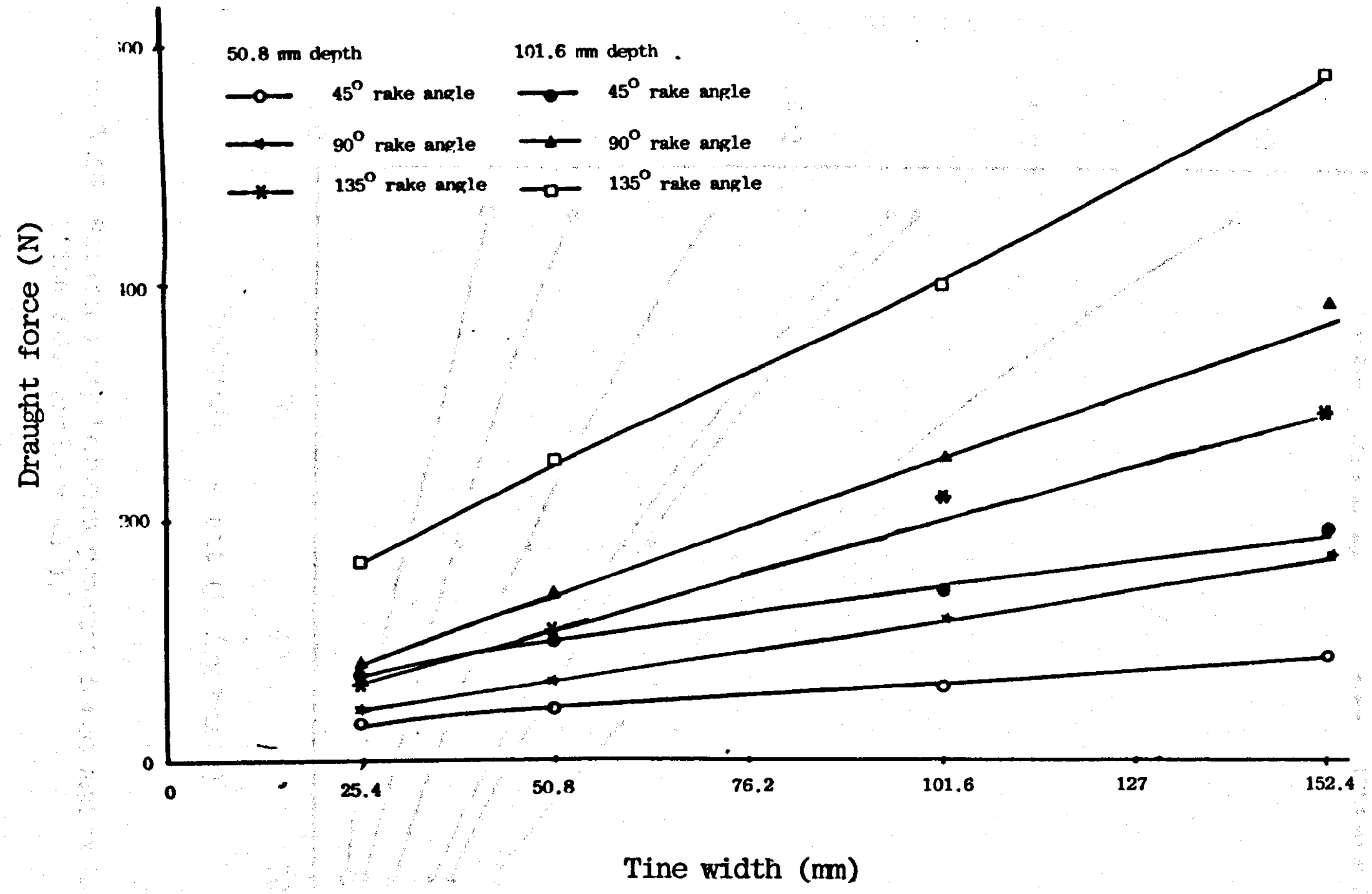


Figure 5.45 Relationship between draught force and tine width (moisture content = 70% dry basis).

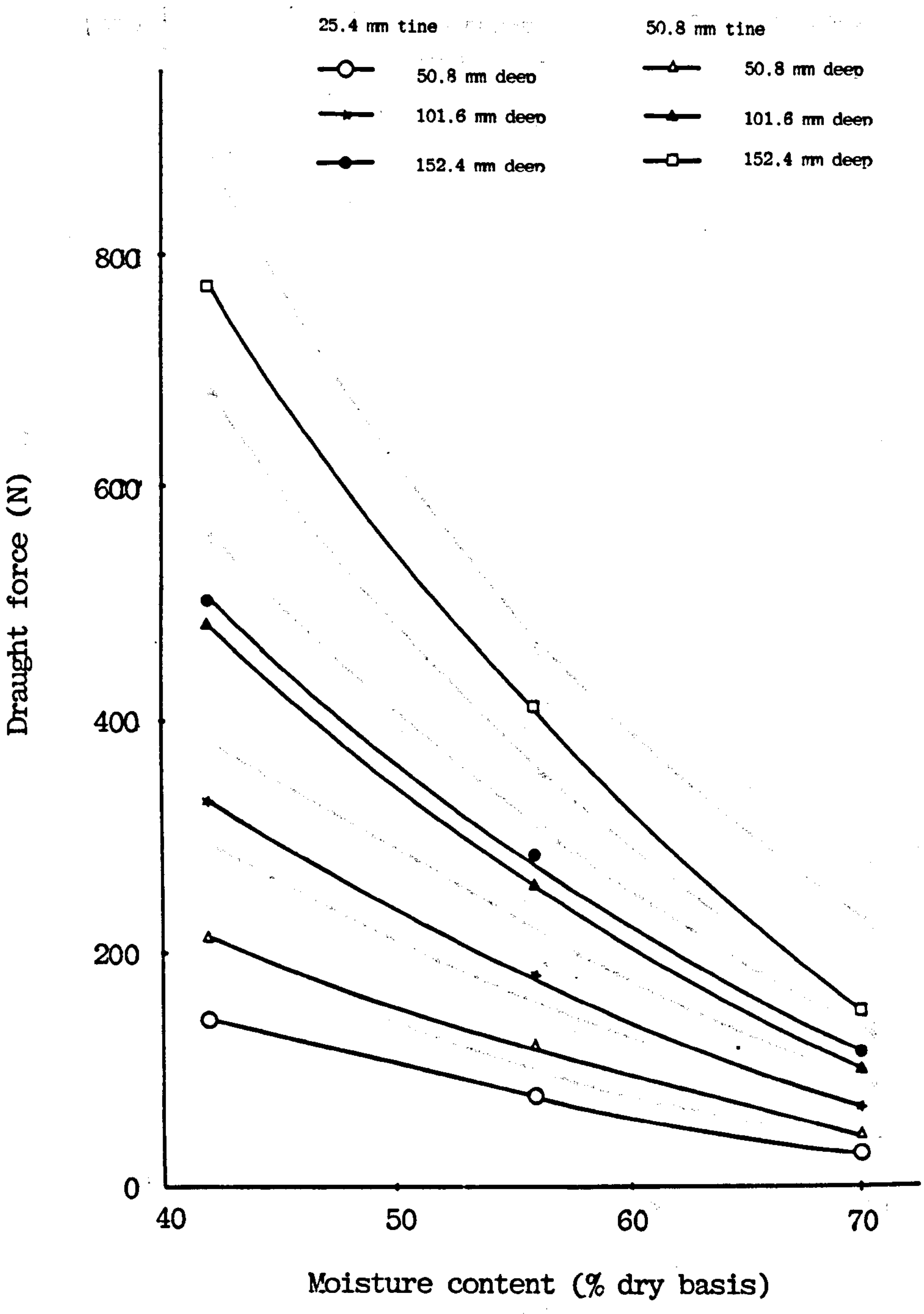


Figure 5.46 Relationship between draught force and moisture content (tine rake angle = 45°).

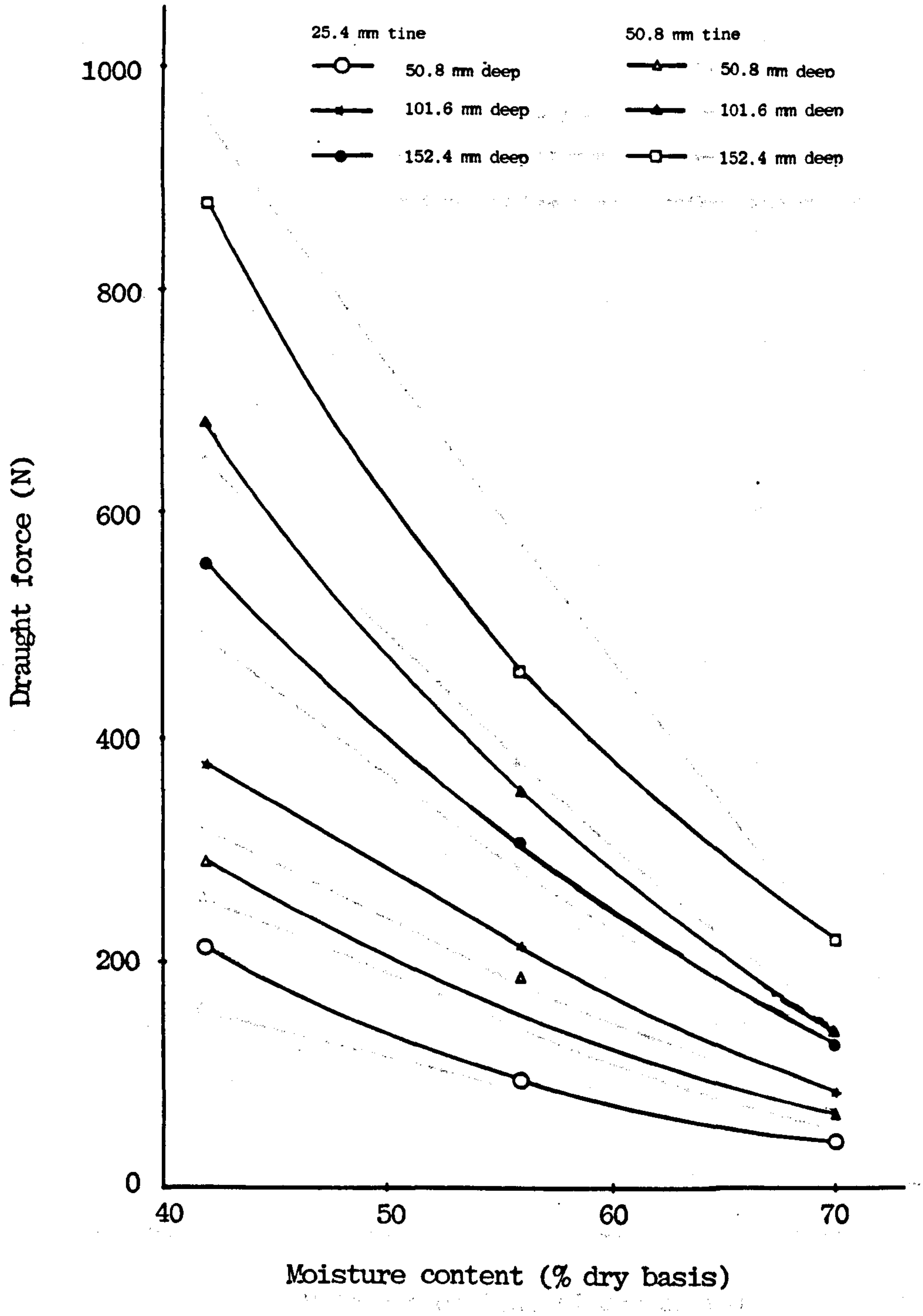


Figure 5.47 Relationship between draught force and moisture content (tine rake angle = 90°).

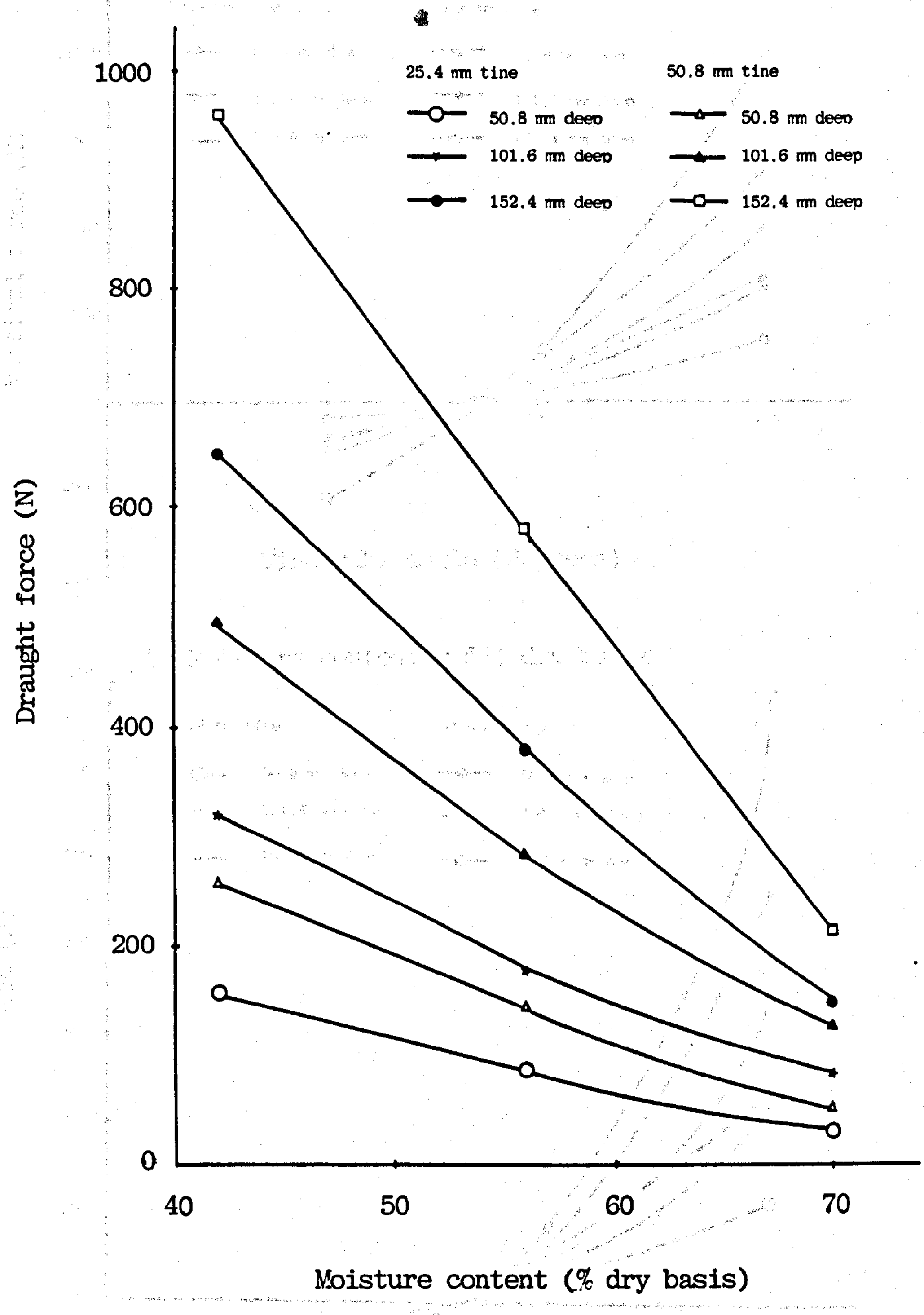


Figure 5.48 Relationship between draught force and moisture content (tine rake angle = 135°).

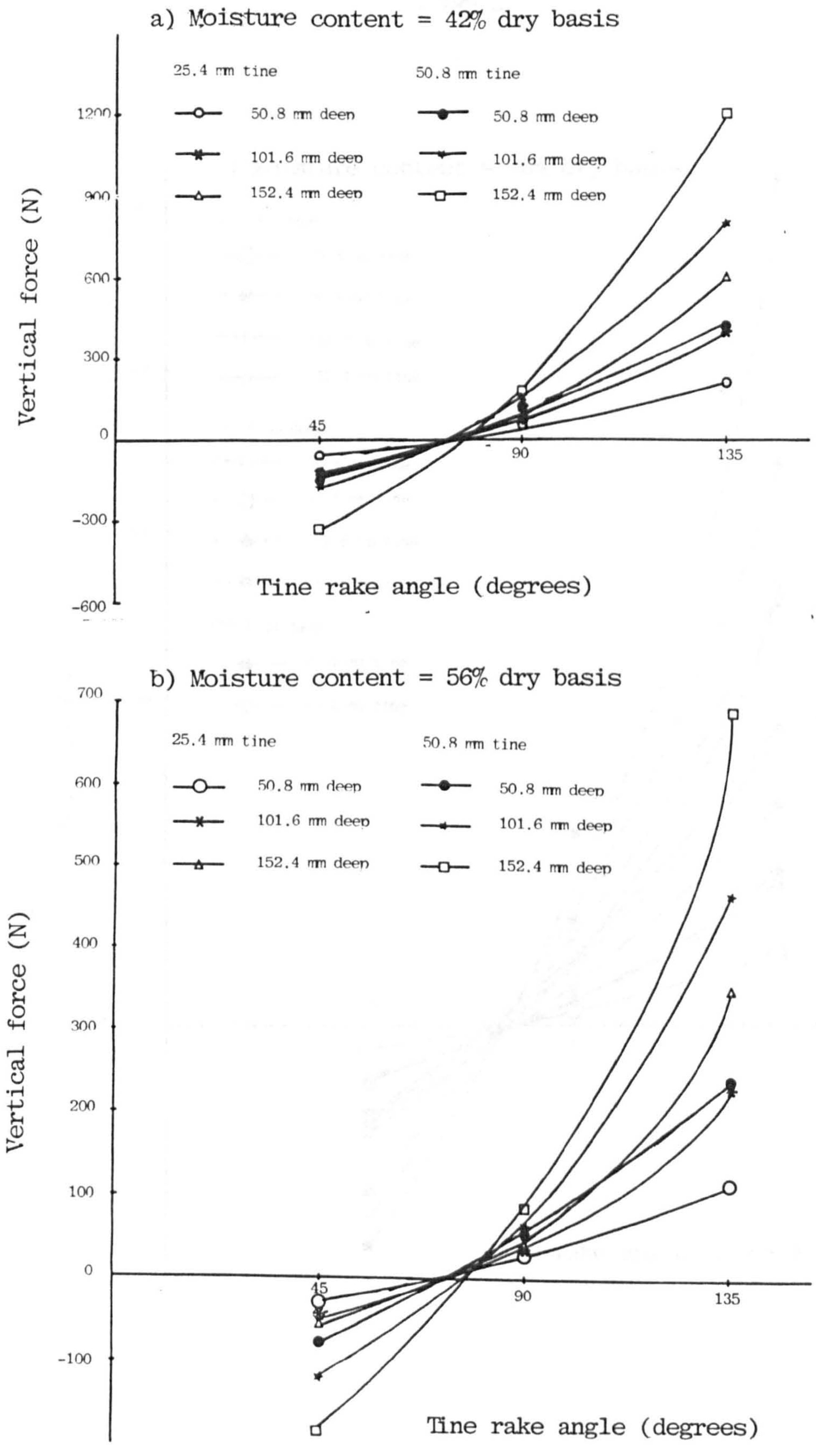
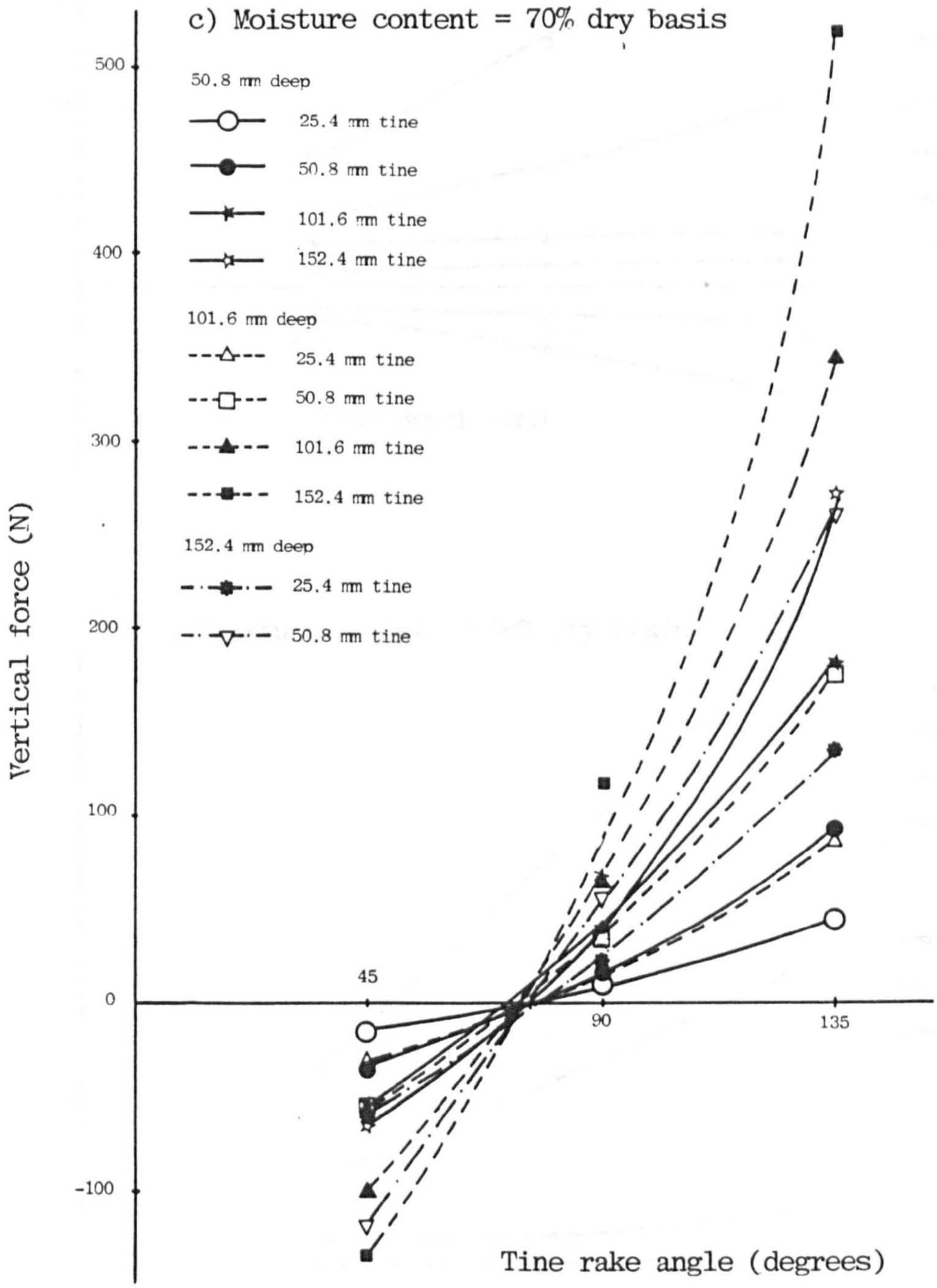
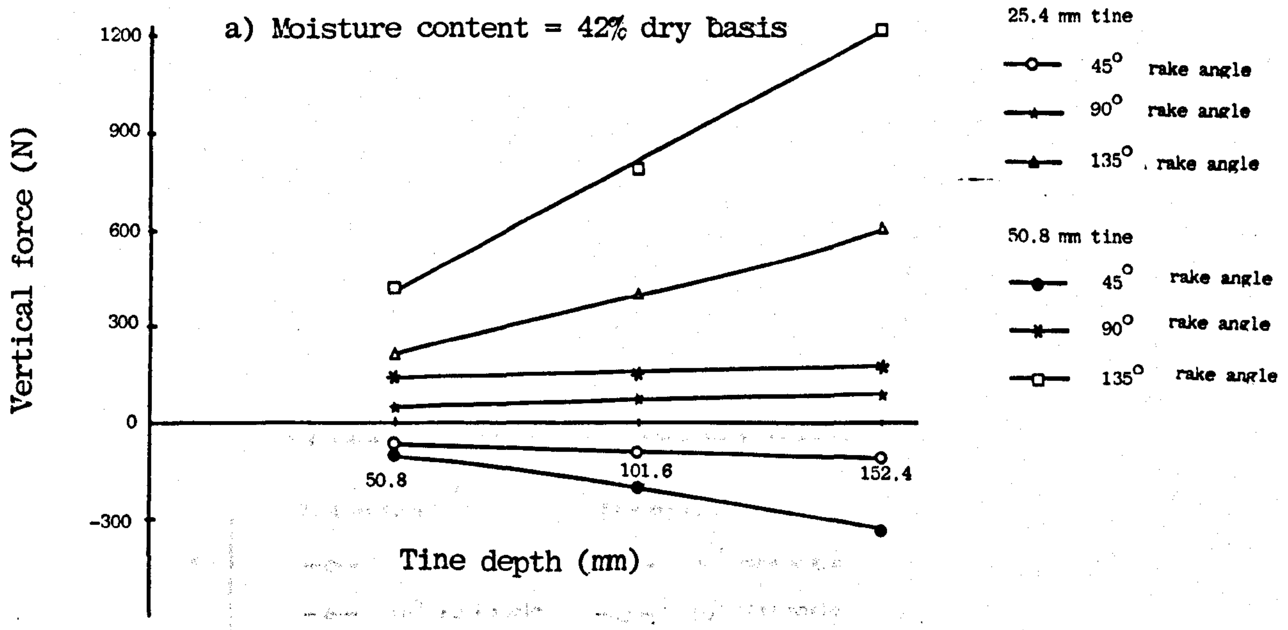


Figure 5.49 Relation of vertical force with tine rake angle.


c) Moisture content = 70% dry basis
50.8 mm deep
25.4 mm tine
50.8 mm tine
101.6 mm tine
152.4 mm tine
101.6 mm deep
25.4 mm tine
50.8 mm tine
101.6 mm tine
152.4 mm tine
152.4 mm deep
25.4 mm tine
50.8 mm tine
Vertical force (N)
500
400
300
200
100
0
-100
45
90
135
Tine rake angle (degrees)



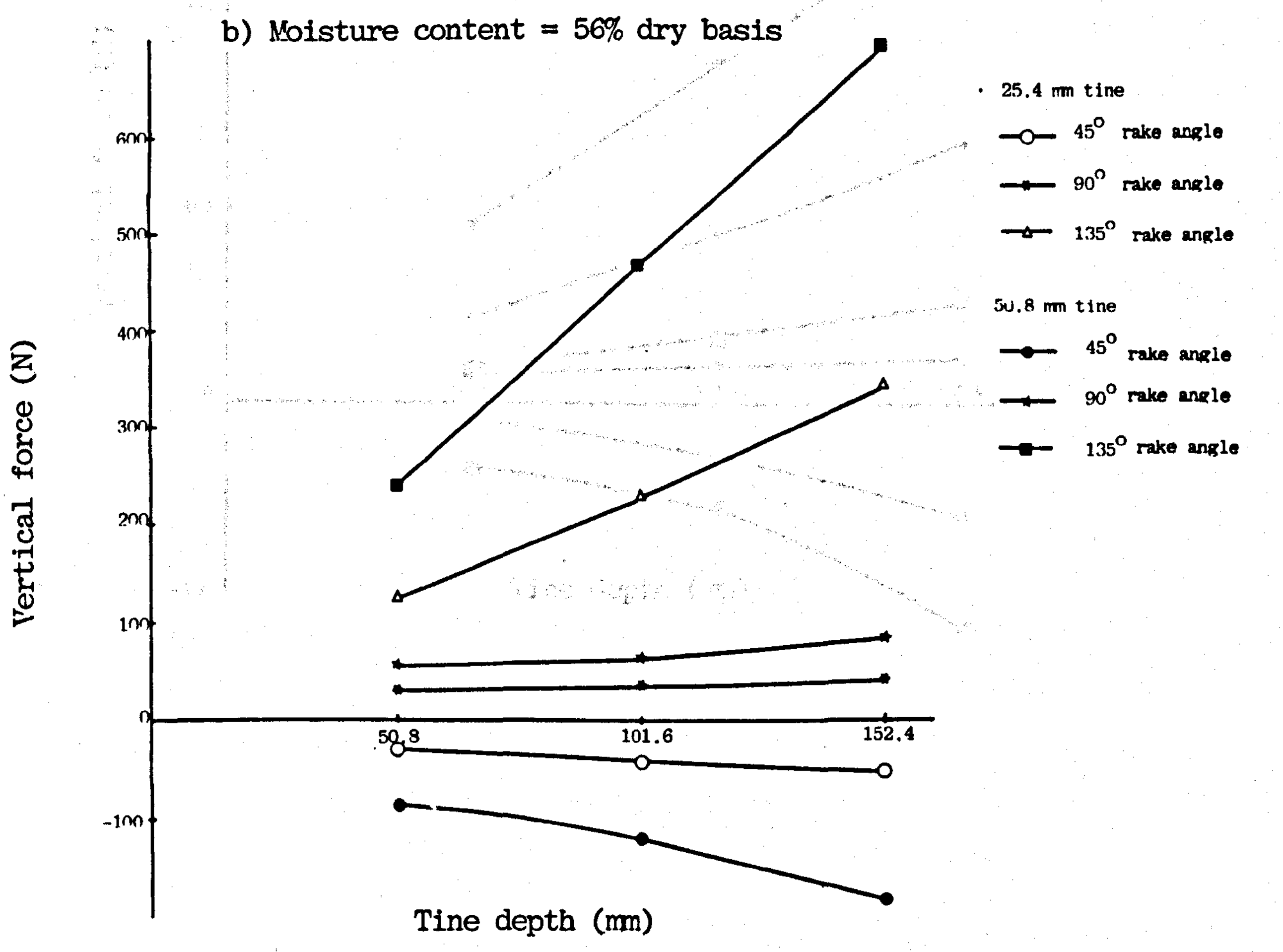
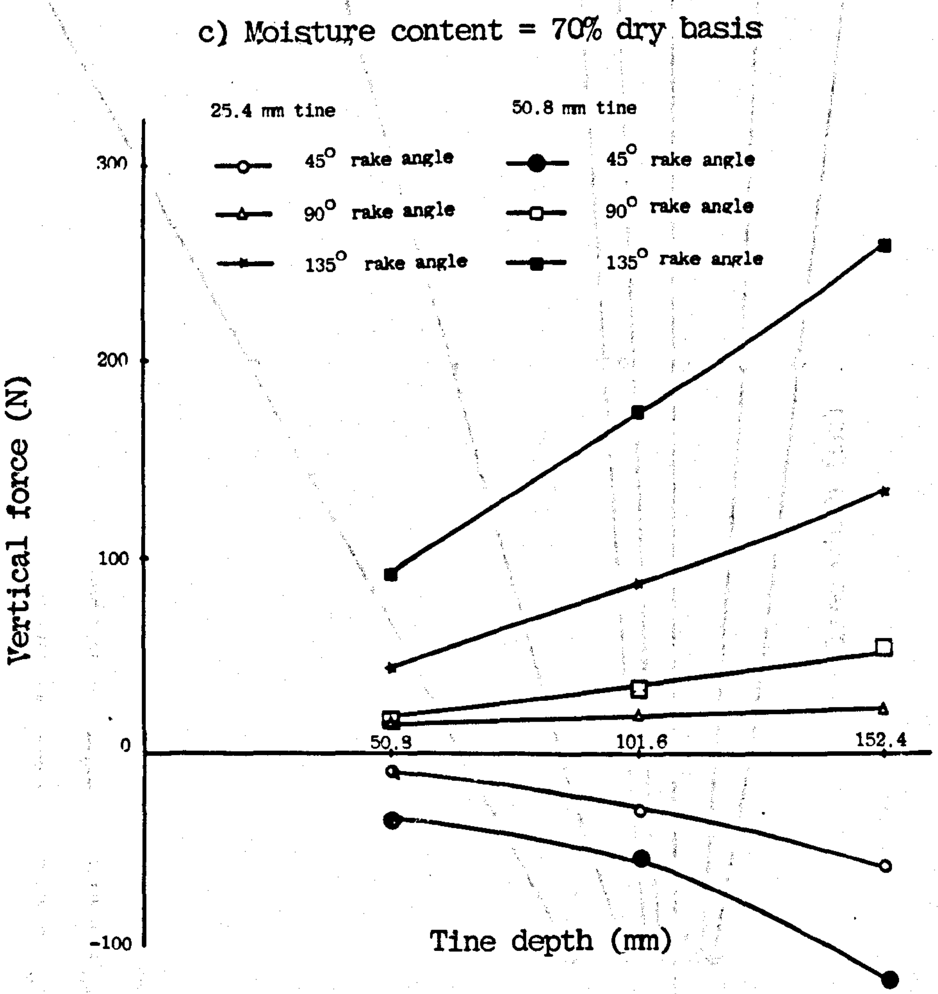


Figure 5.50 Relation of vertical force with tine depth.


c) Moisture content = 70% dry basis
25.4 mm tine
45° rake angle
90° rake angle
135° rake angle
50.8 mm tine
45° rake angle
90° rake angle
135° rake angle
Vertical force (N)
300
200
100
0
-100
50.8
101.6
152.4
Tine depth (mm)

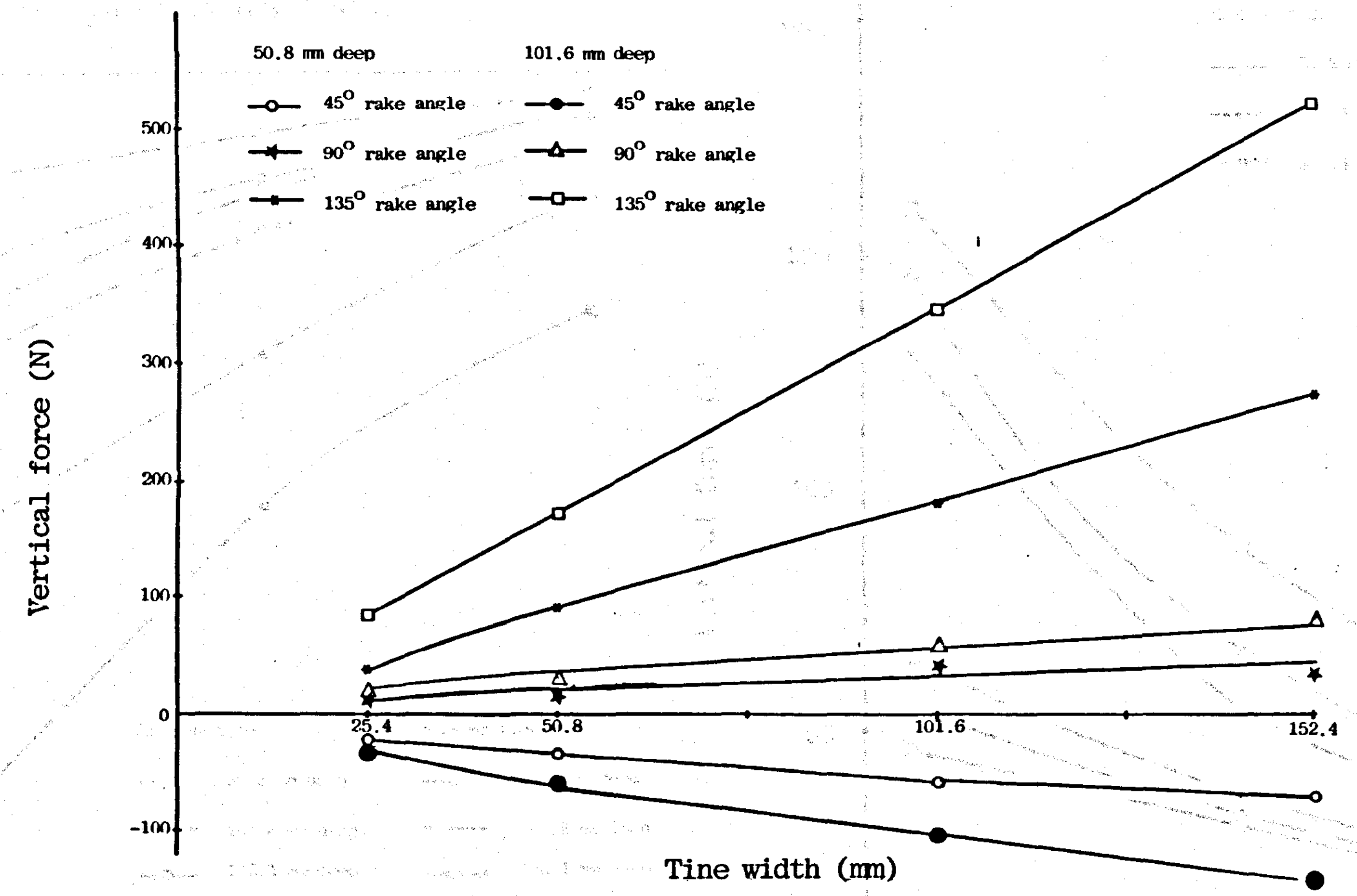


Figure 5.51 Relation of vertical force with tine width.

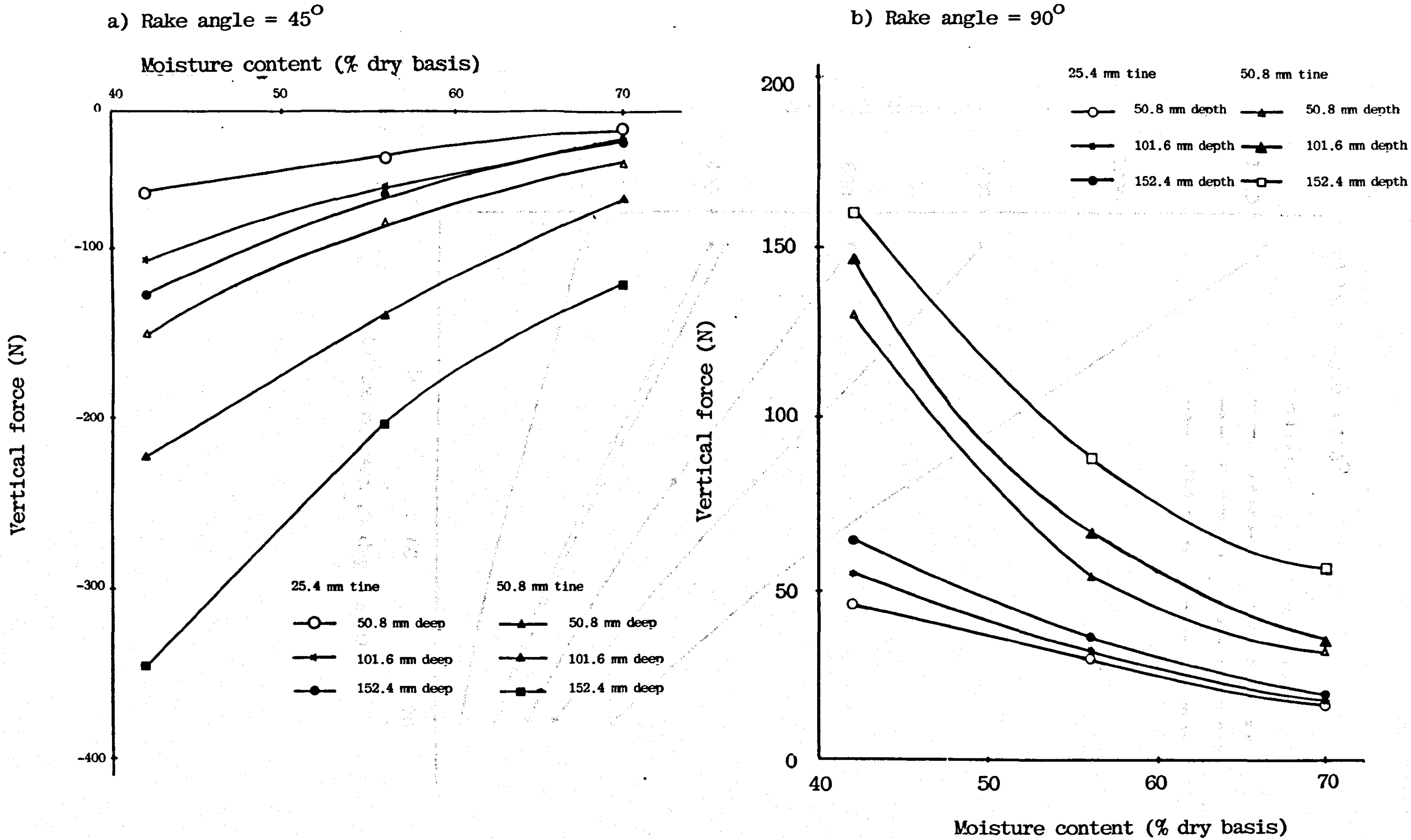
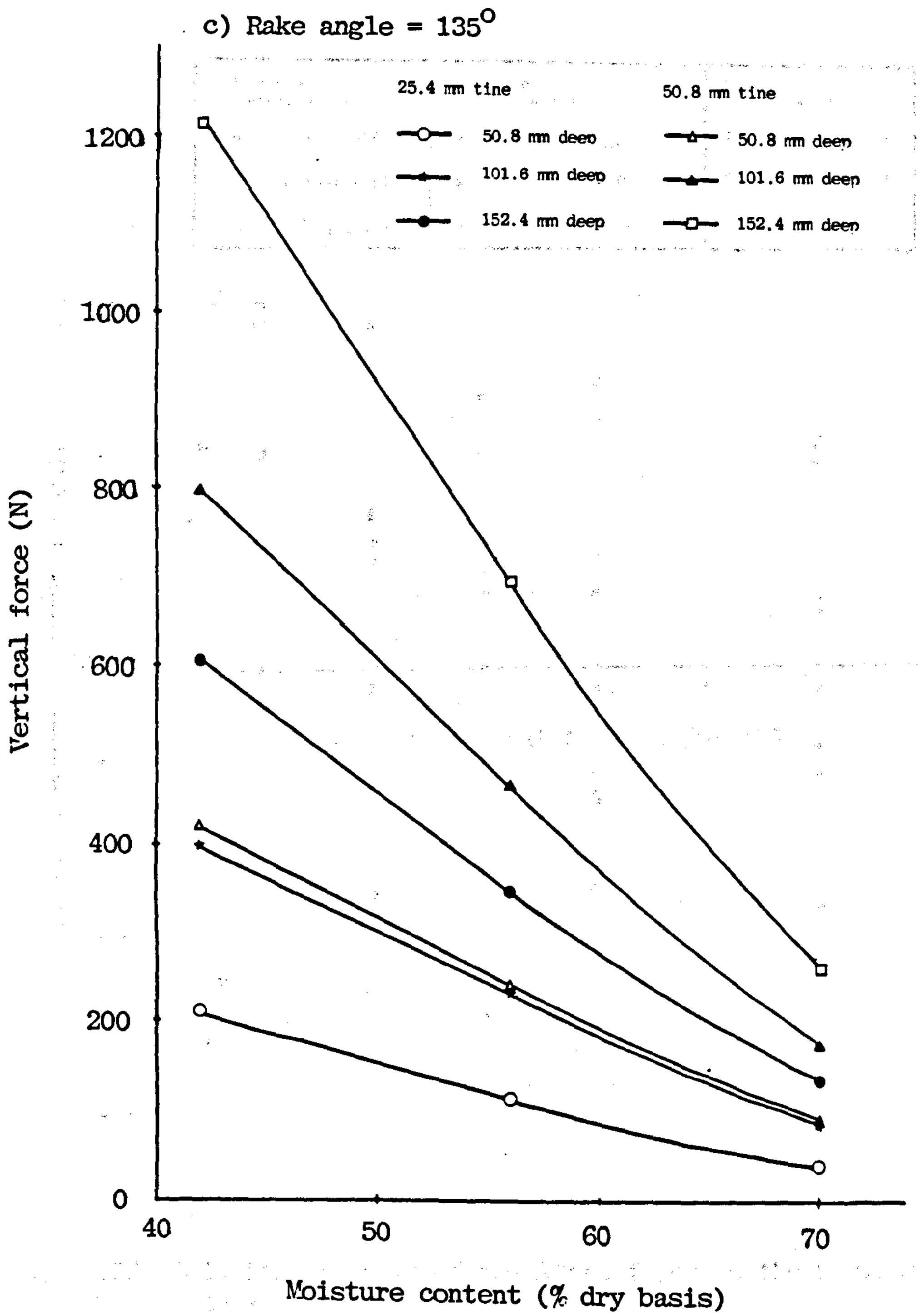


Figure 5.52 Relation of vertical force with moisture content.


c) Rake angle = 135°
25.4 mm tine
50.8 mm deep
101.6 mm deep
152.4 mm deep
50.8 mm tine
50.8 mm deep
101.6 mm deep
152.4 mm deep
Vertical force (N)
0
200
400
600
800
1000
1200
40
50
60
70
Moisture content (% dry basis)

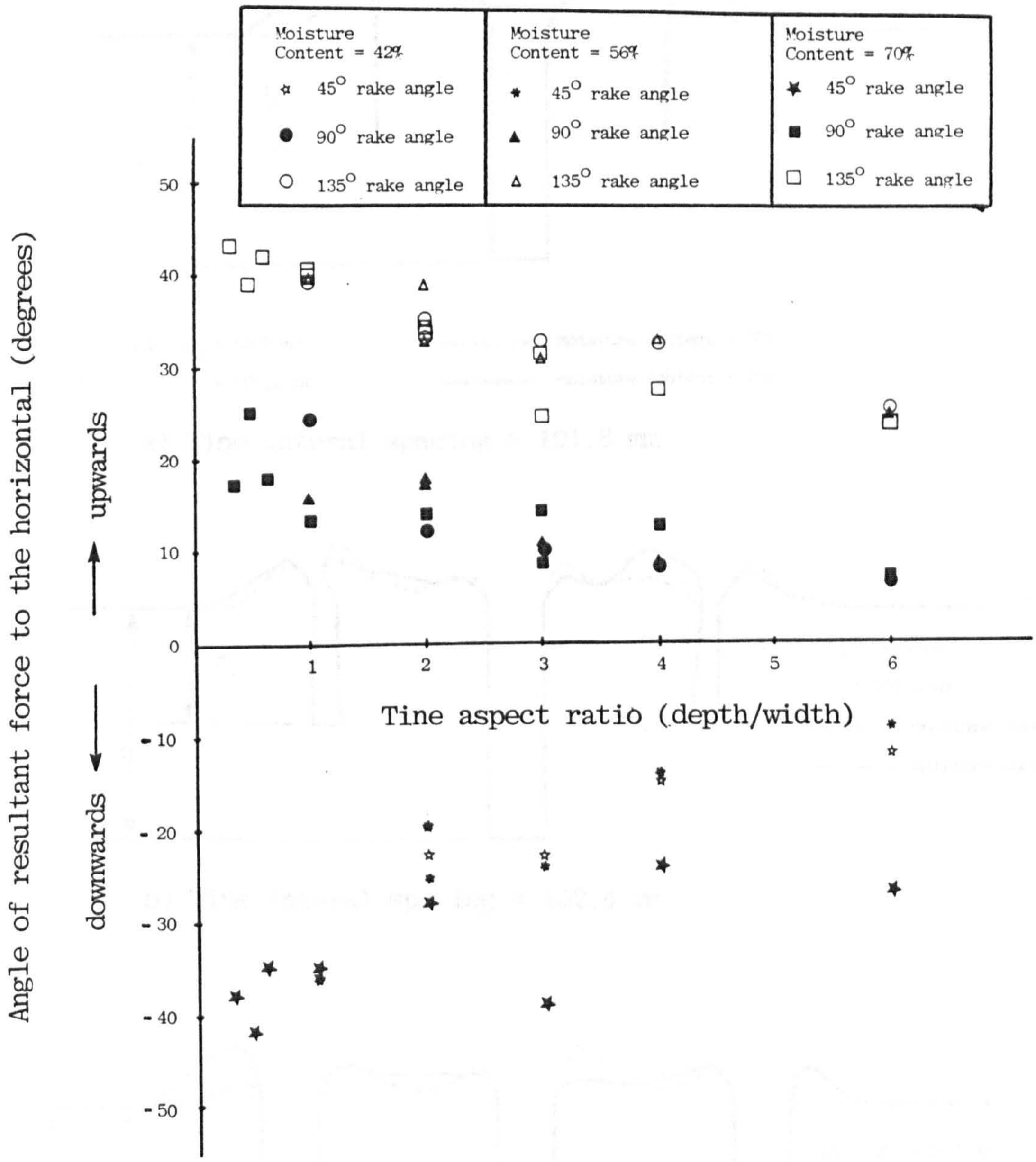
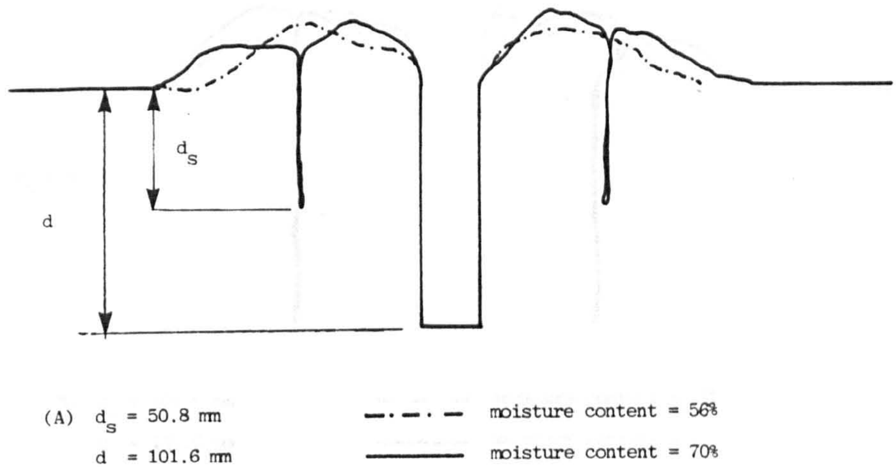
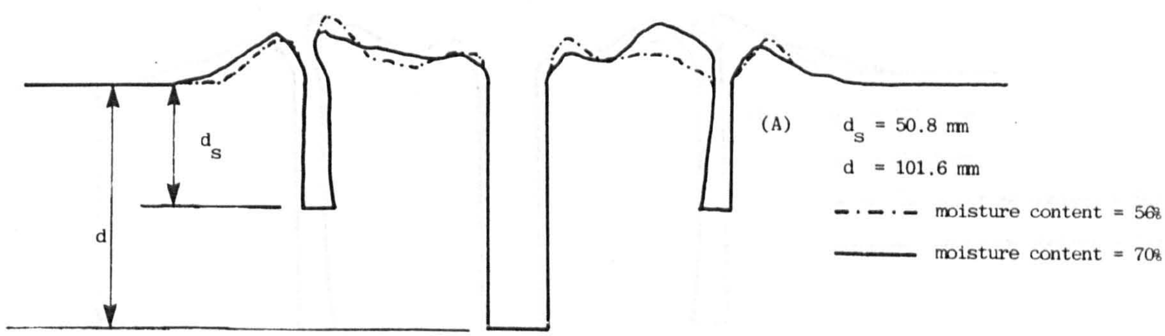


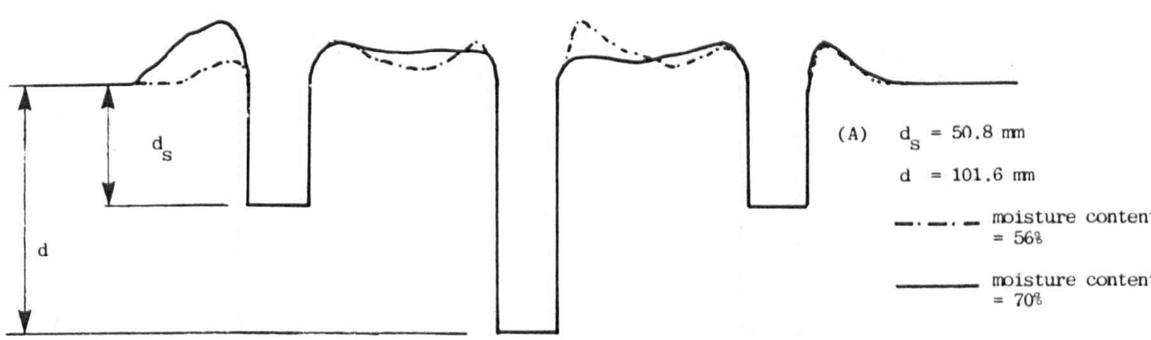
Figure 5.53 Relation of angle of resultant force to the horizontal with tine aspect ratio.



a) Tine lateral spacing = 101.6 mm

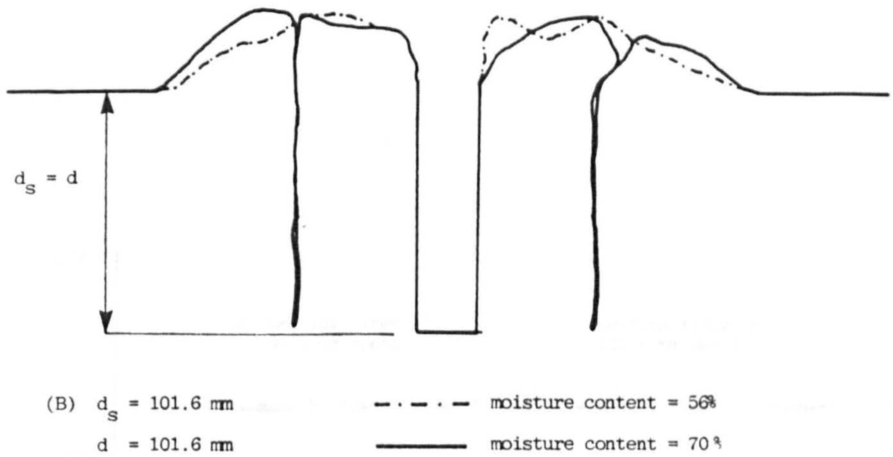


b) Tine lateral spacing = 152.4 mm

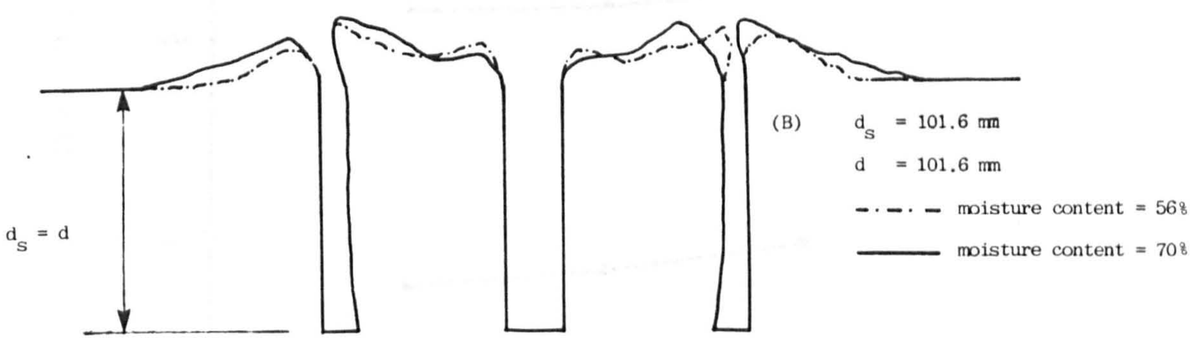


c) Tine lateral spacing = 203.2 mm

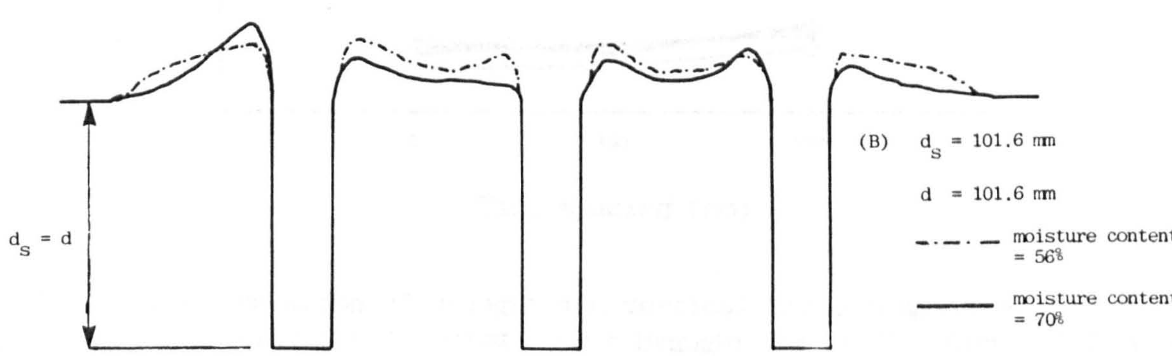
Figure 5.54 Profile of soil disturbance by multiple tines (leading tines at 50.8 mm depth).



a) Tine lateral spacing = 101.6 mm



b) Tine lateral spacing = 152.4 mm



c) Tine lateral spacing = 203.2 mm

Figure 5.55 Profile of soil disturbance by multiple tines (leading tines at 101.6 mm depth).

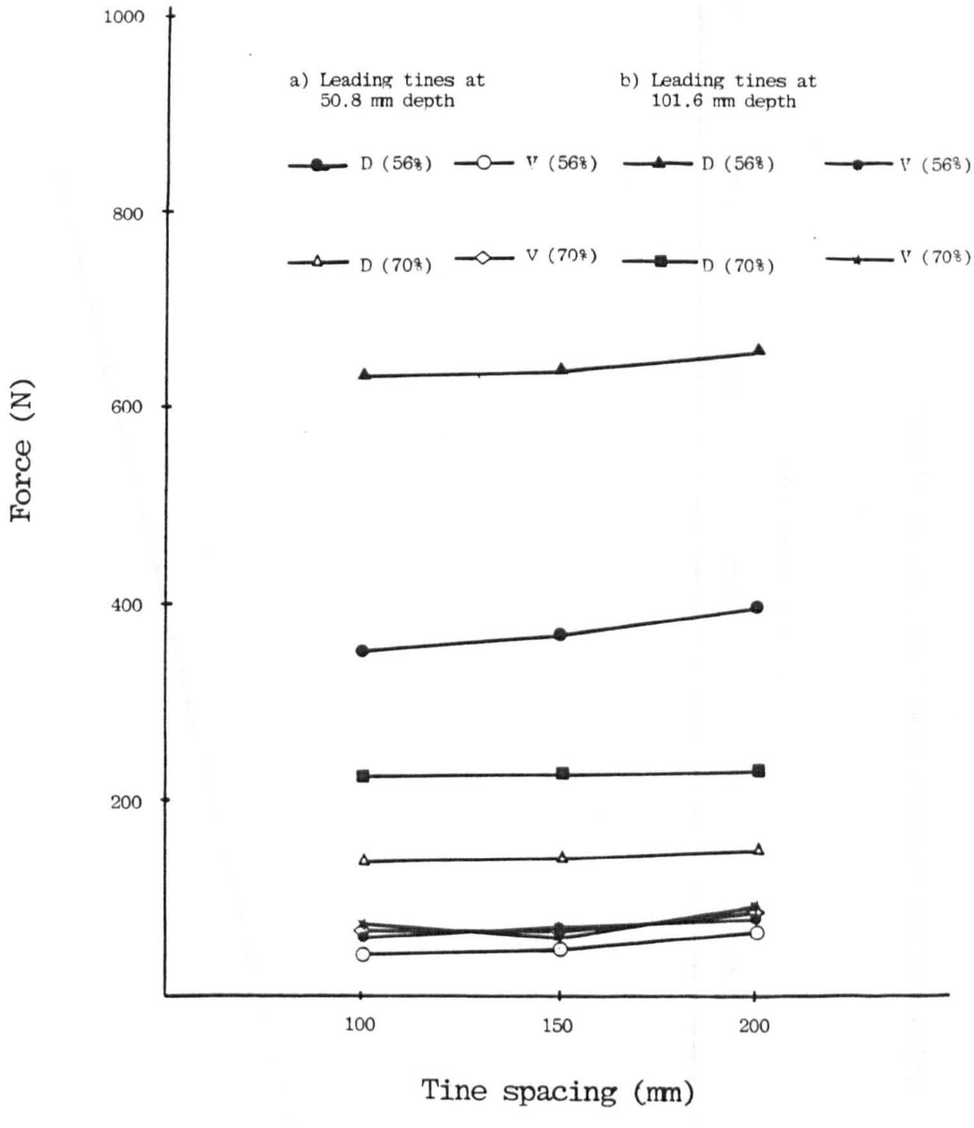


Figure 5.56 Relation of draught and vertical force components with tine spacing. (D = Draught force, V = Vertical force).

Figures in brackets are percentage moisture content (dry basis).

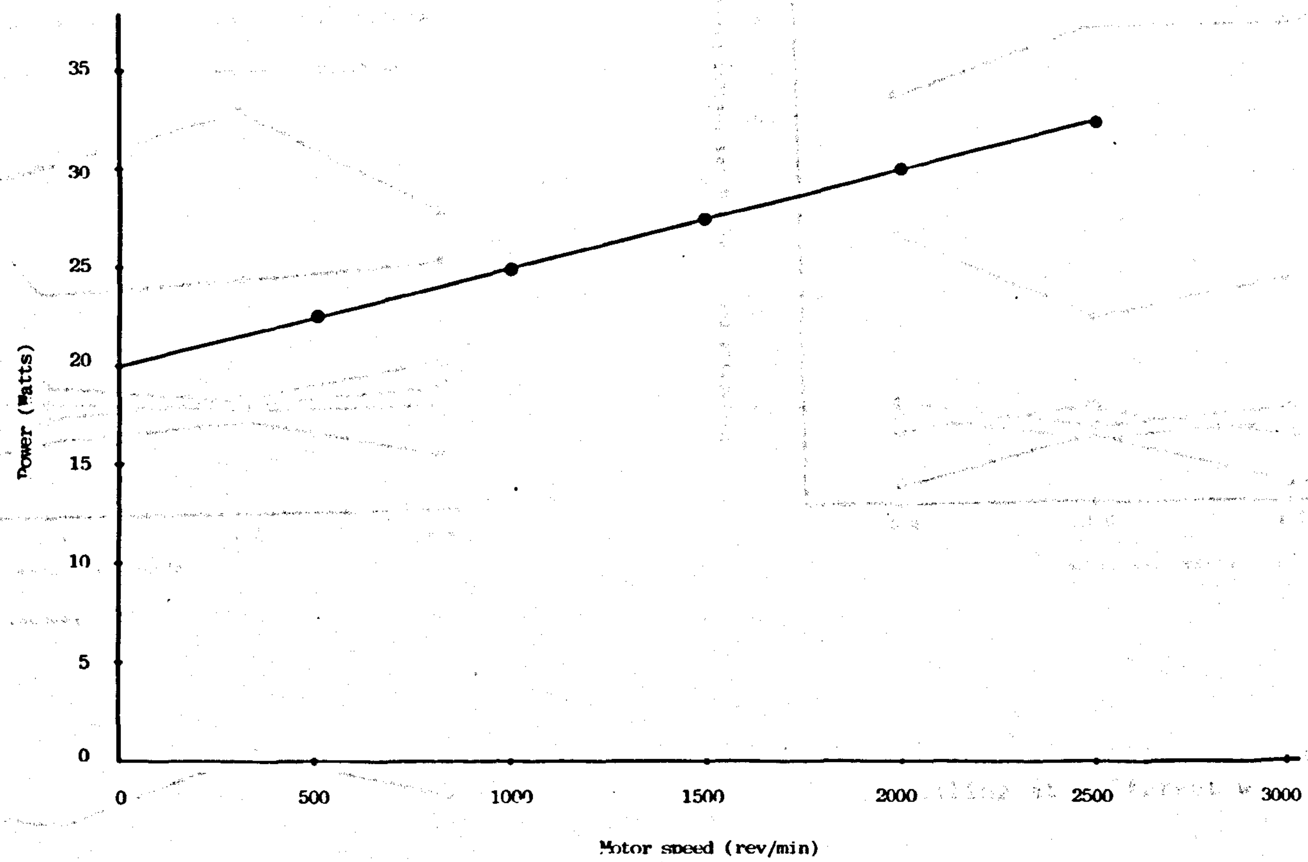


Figure 5.57 Relationship between power and motor speed.

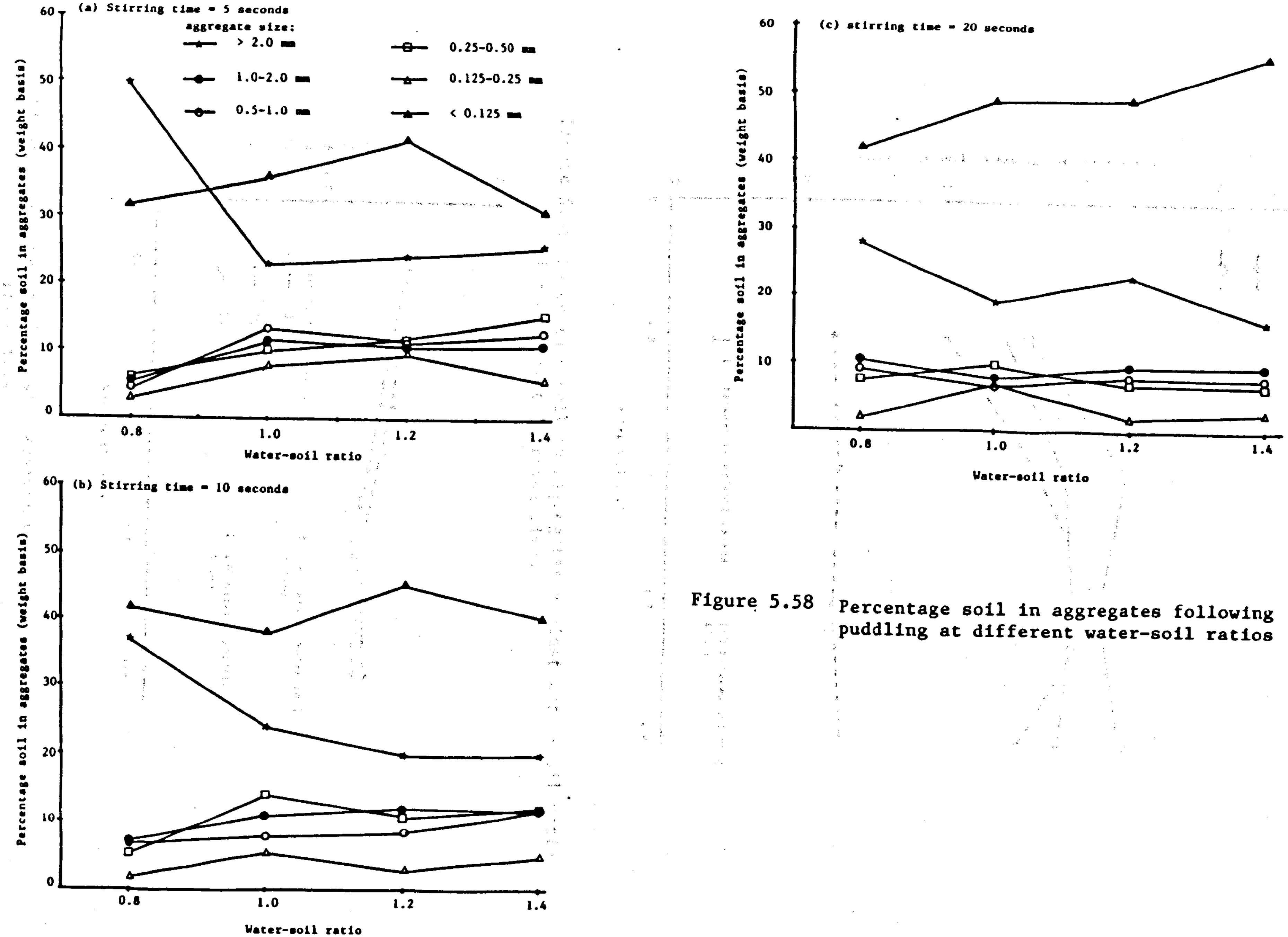


Figure 5.58 Percentage soil in aggregates following puddling at different water-soil ratios

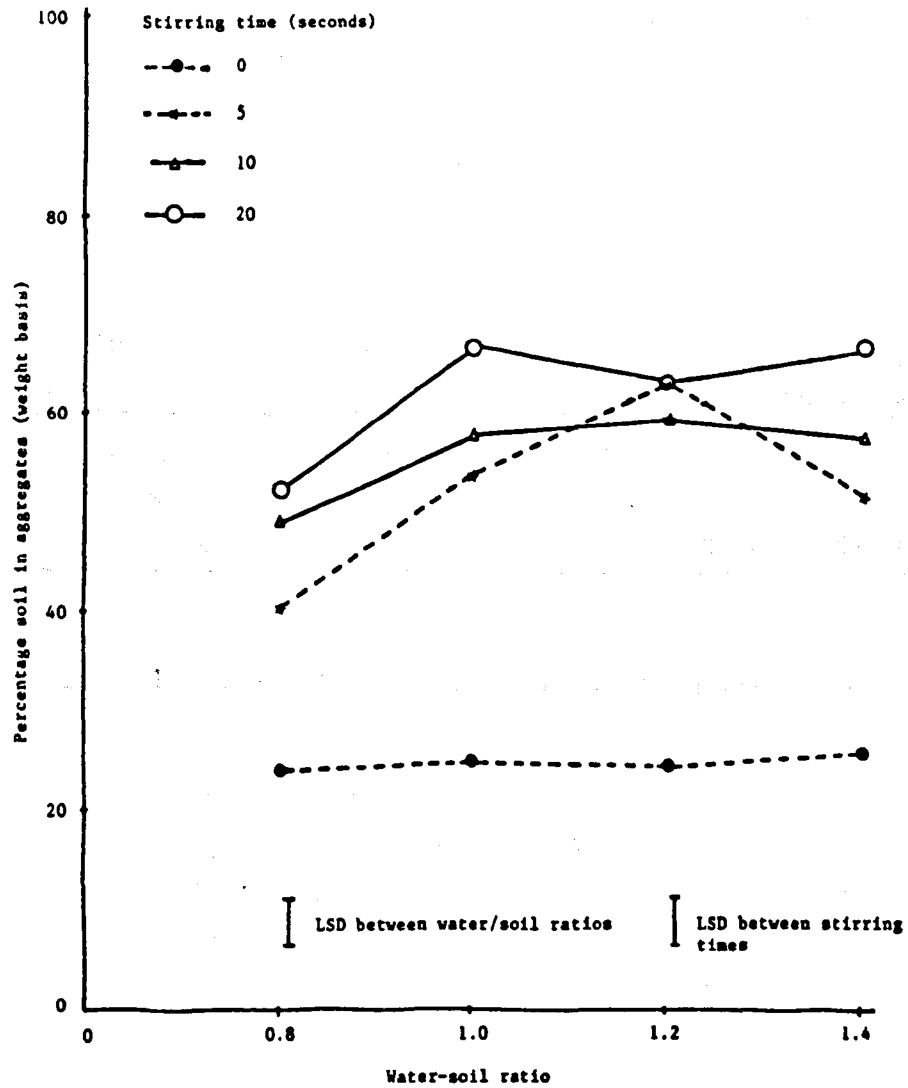


Figure 5.59 Percentage soil in aggregates against water-soil ratio for different stirring times

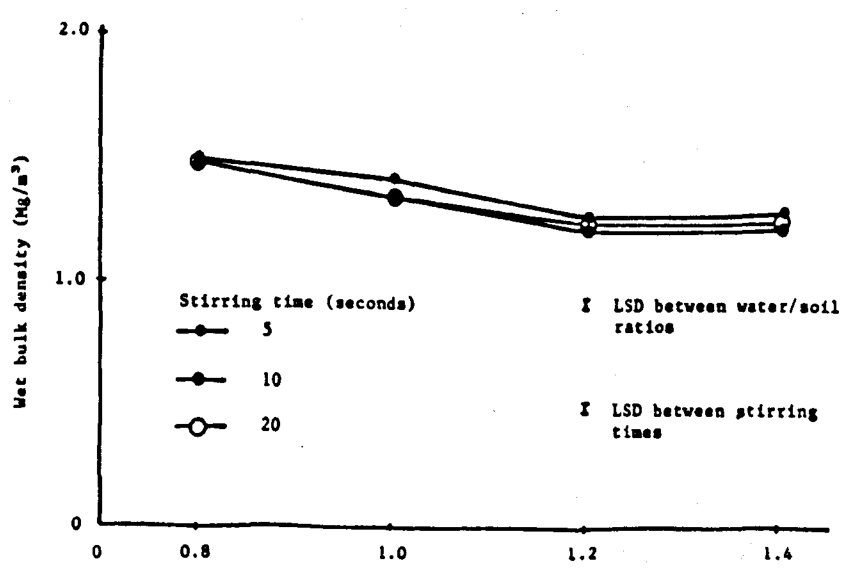


Figure 5.60 Wet bulk density against water-soil ratio for different stirring times

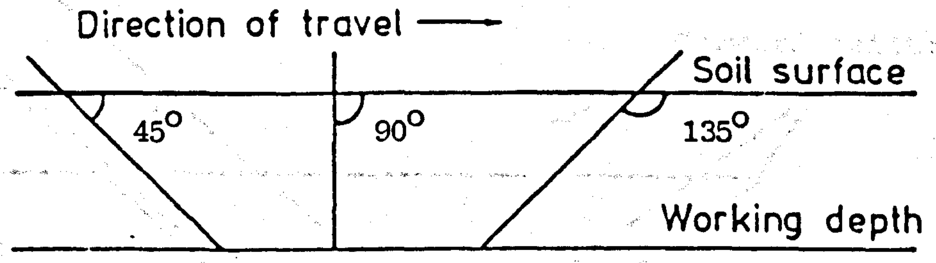


Figure 6.1 Tine inclination angle in the direction of travel.

(a) Wide tine

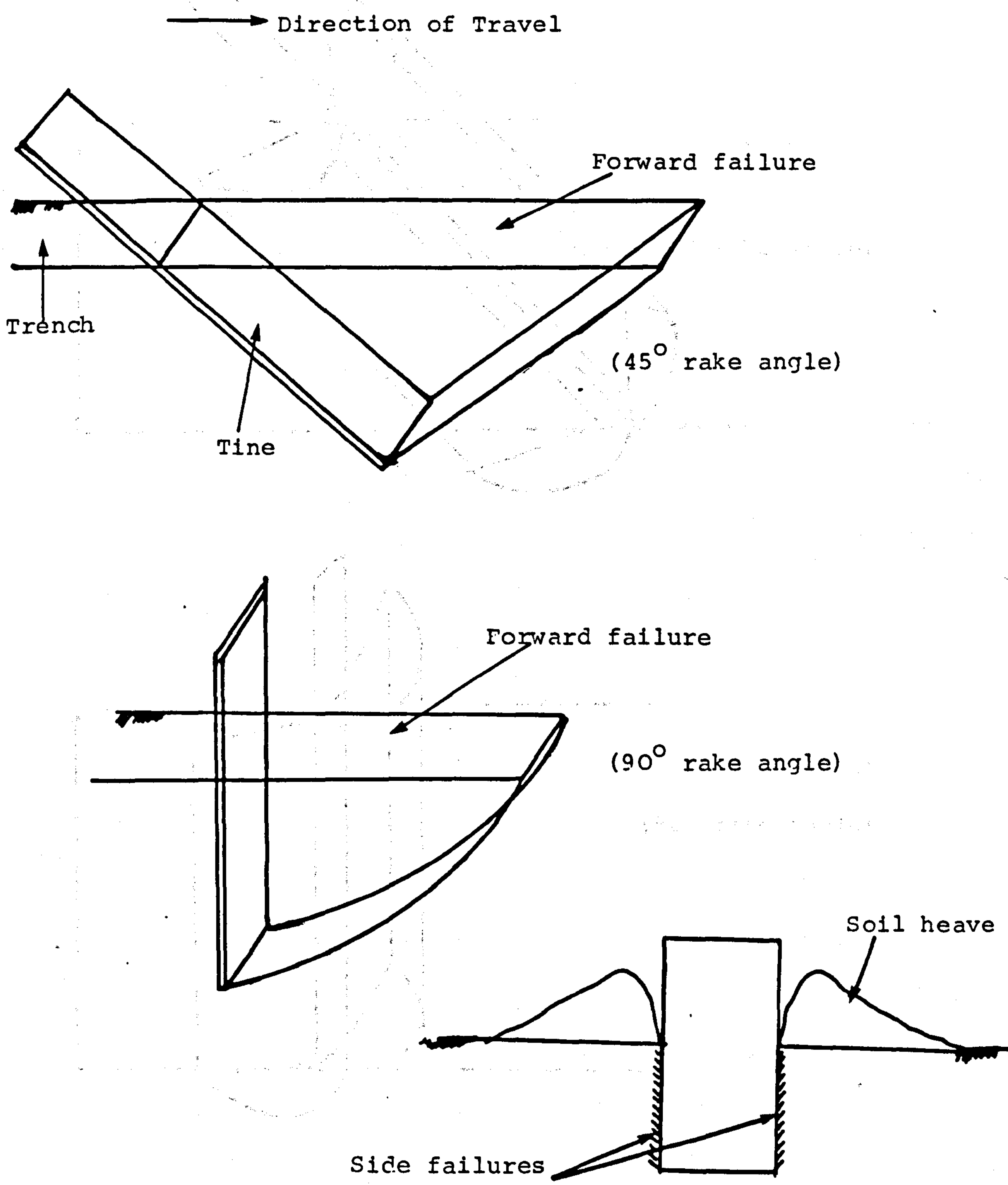
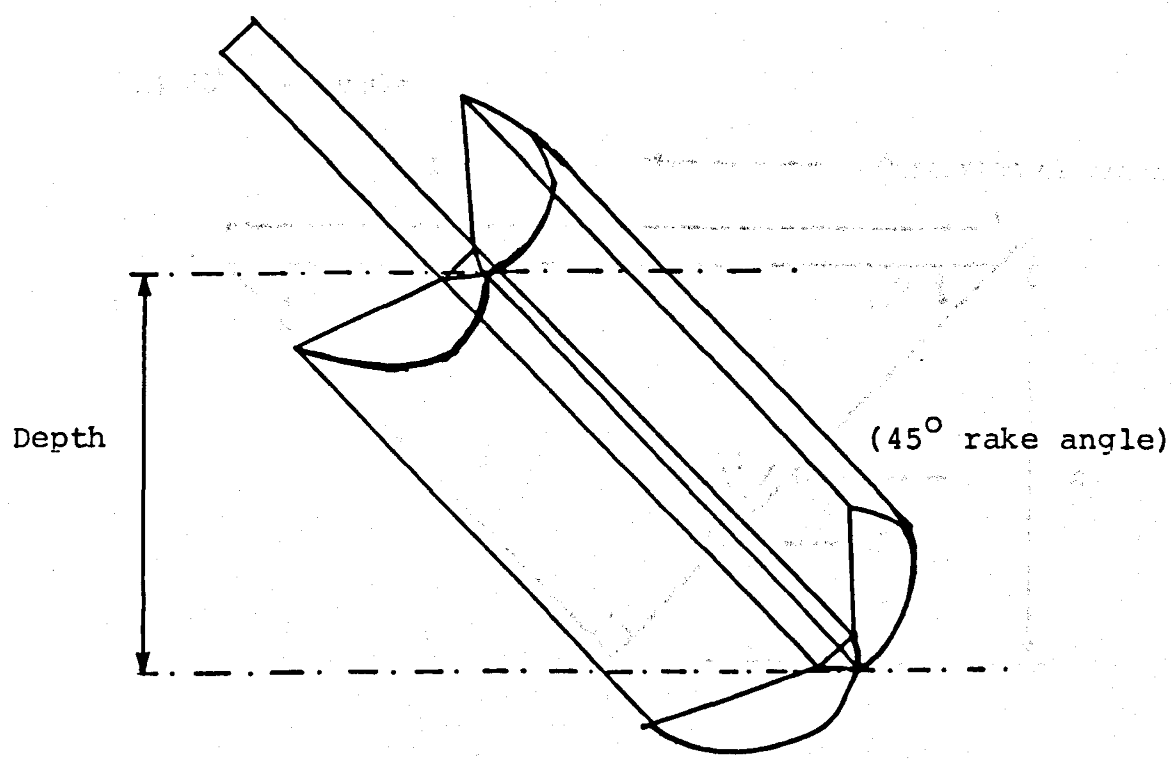


Figure 6.2 Assumed soil failure patterns for 45° and 90° rake angle tines.

(b) Narrow tine



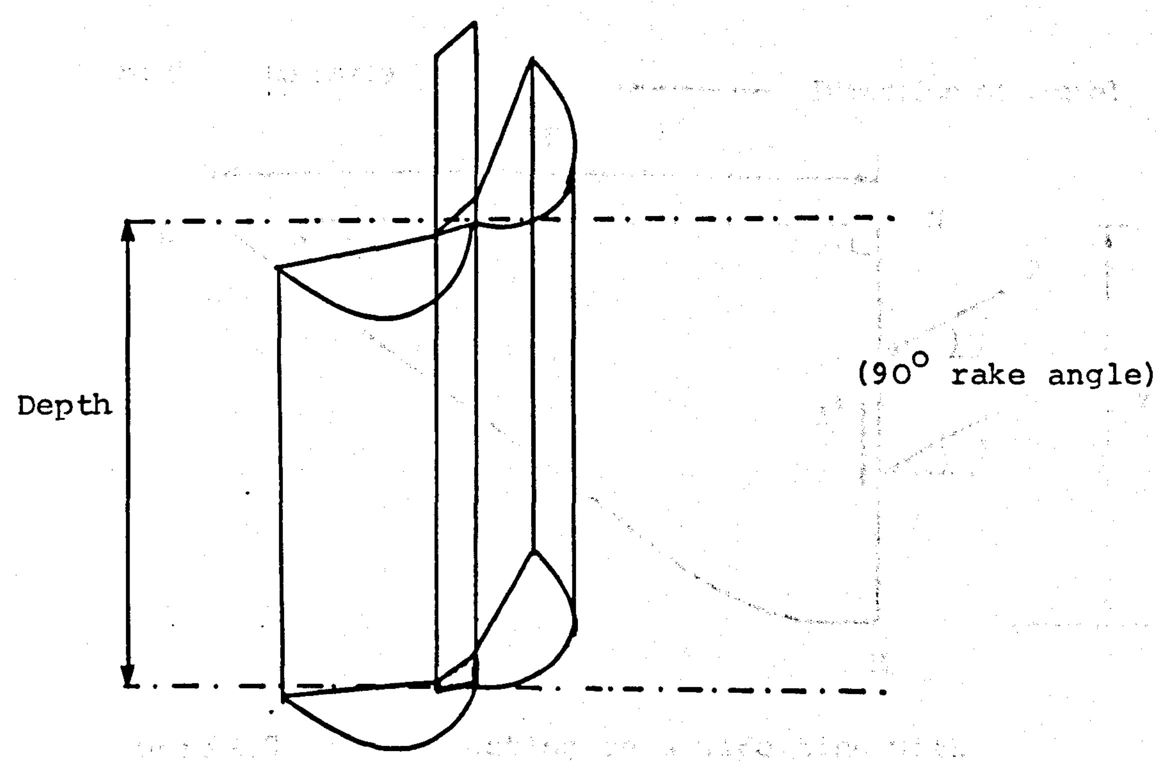
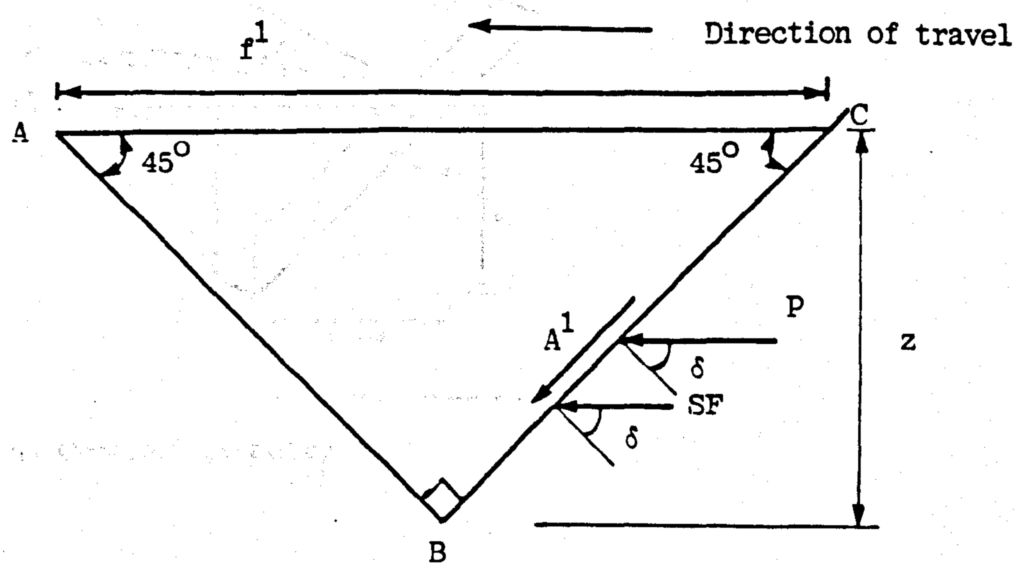


Figure 6.2 (continued).

a) 45° rake angle



b) 90° rake angle

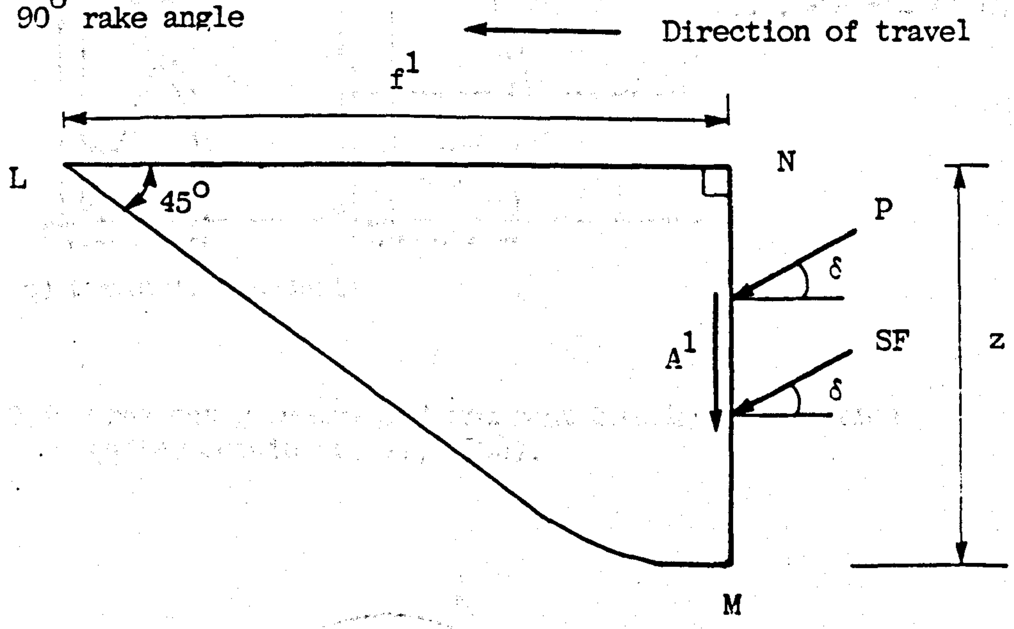
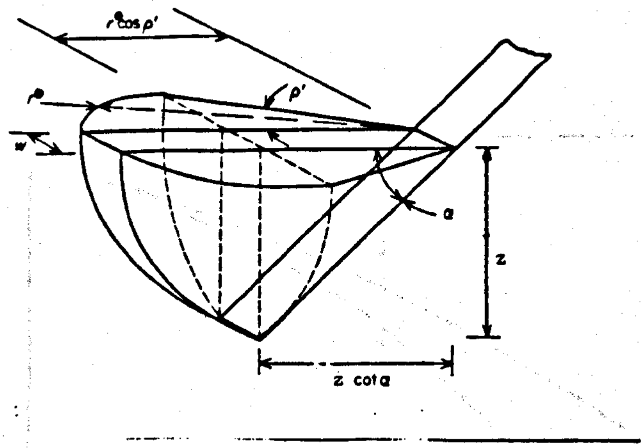
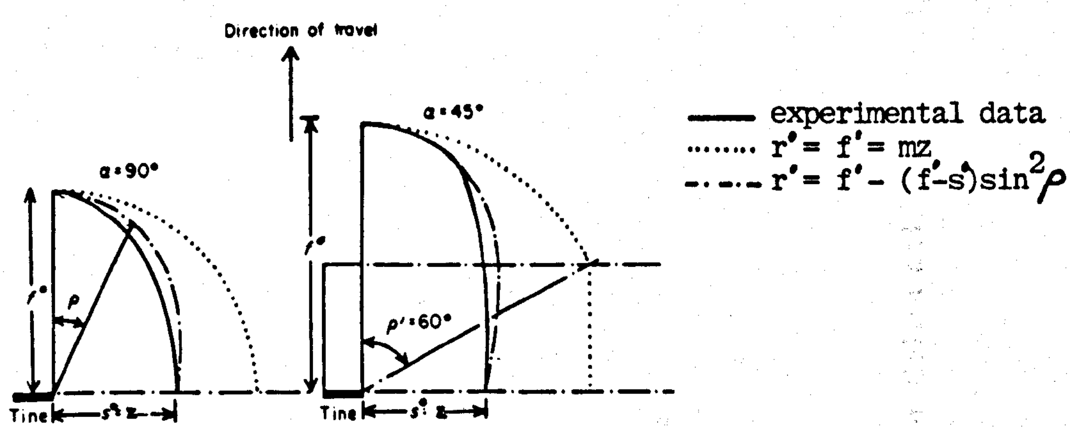


Figure 6.3 Forces acting on a wide tine with 45° and 90° rake angles.

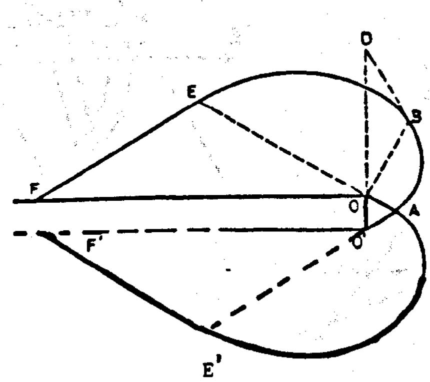


a) Crescent geometry



b) Crescent boundaries

Figure 6.4 Crescent geometry and crescent boundary estimation (after Godwin et. al, 1985).



(Plan view)

Figure 6.5 Idealized failure geometry for a narrow tine in wet soil. (Tine rake angle=90^0).

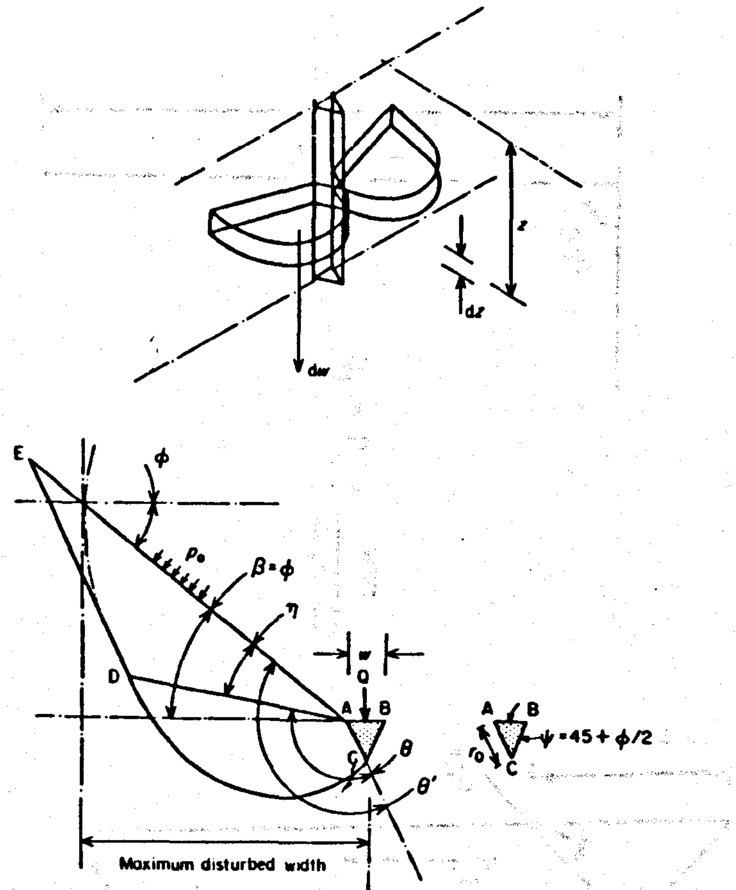


Figure 6.6 Lateral soil failure mechanism (after Godwin and Spoor, 1977).

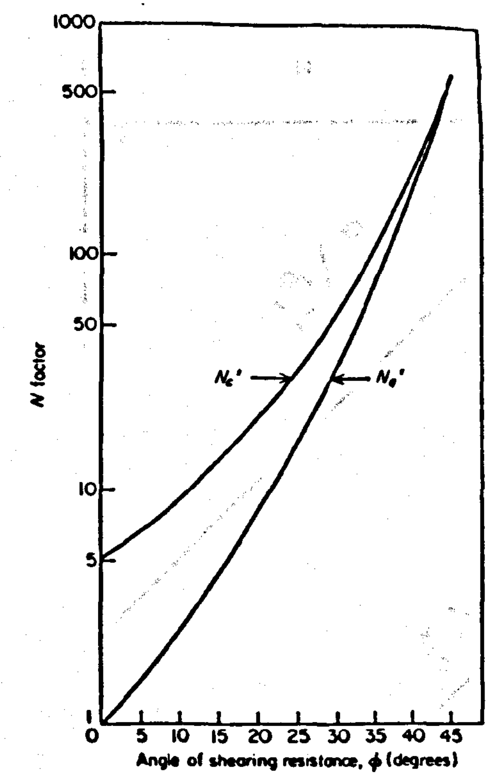


Figure 6.7 Dimensionless N factors for lateral soil failure (after Godwin and Spoor, 1977).

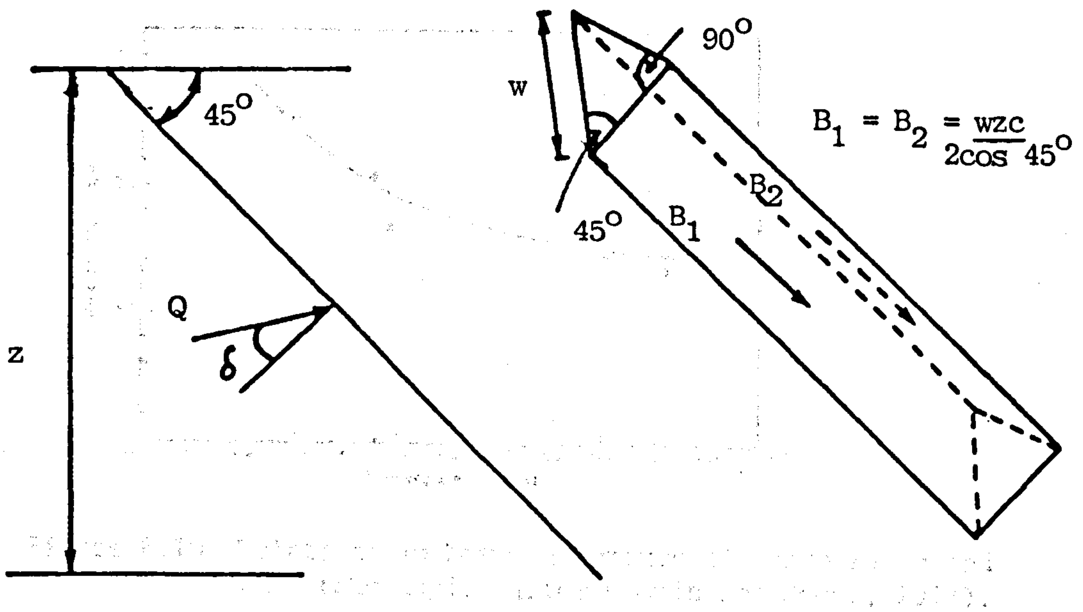


Figure 6.8 Forces on a narrow tine with 45° rake angle

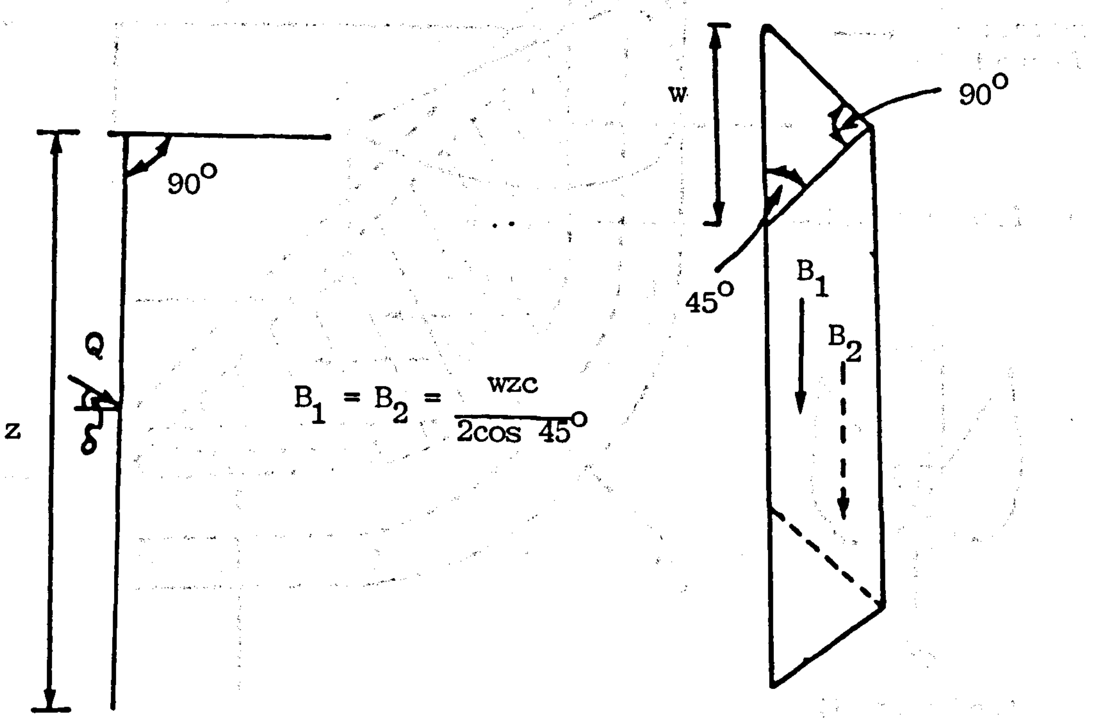


Figure 6.9 Forces on a narrow tine with 90° rake angle

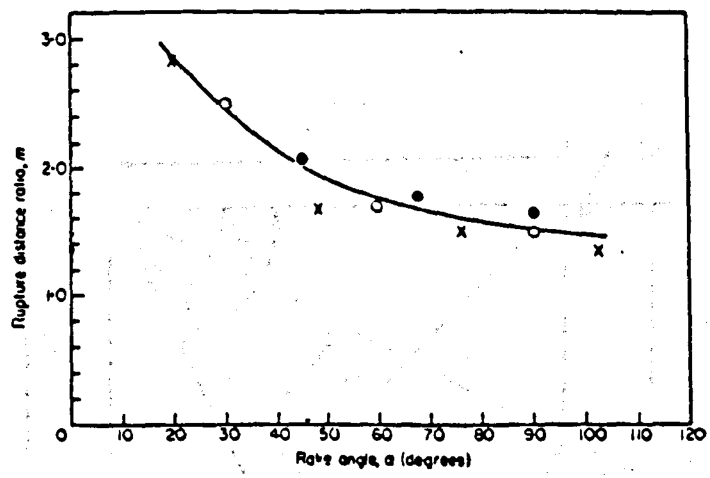


Figure 6.10 Relationship between rupture distance ratio and tine rake angle (after Godwin and Spoor, 1977).

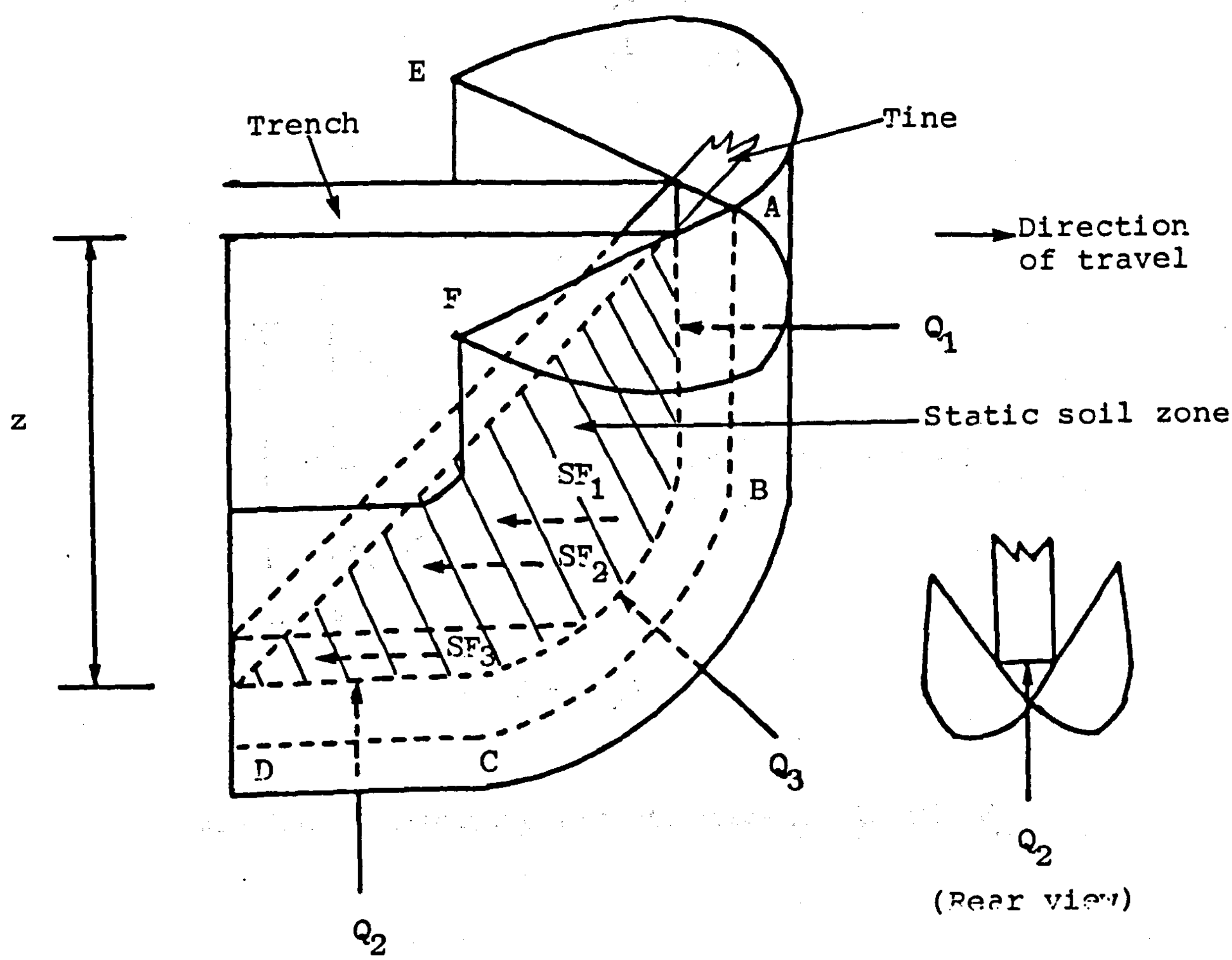
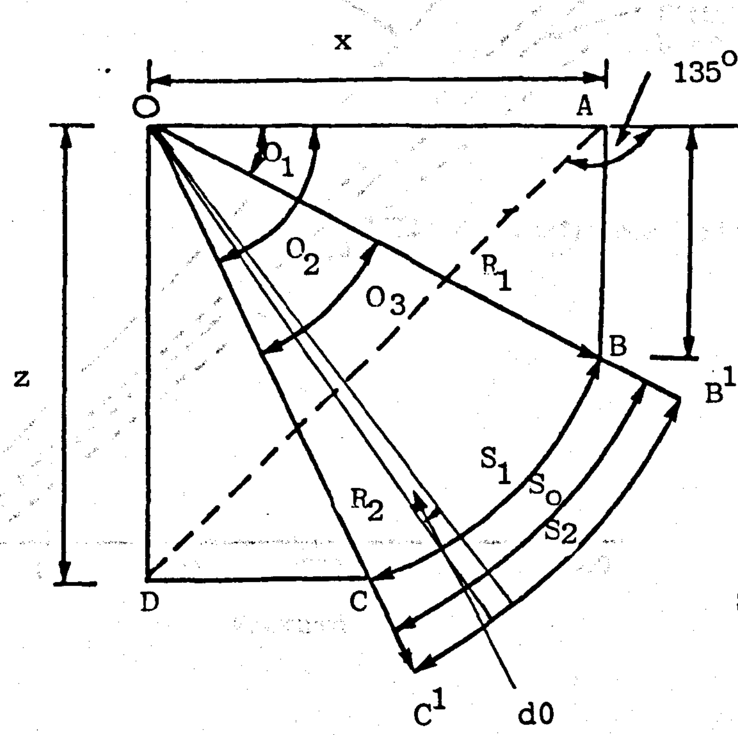
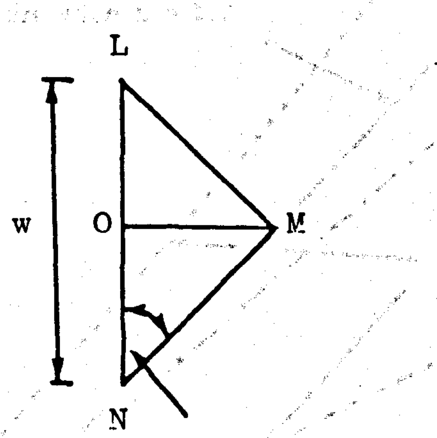


Figure 6.11 Idealized failure pattern and the acting forces for a backward raked tine.



$$S_o = (S_1 + S_2)/_2$$



$$OM = \frac{w}{2} \tan\,(45 + \phi/_2)$$

$$\psi = (45 + \phi/_2)$$

Figure 6.12 Determination of effective arc length, S_o

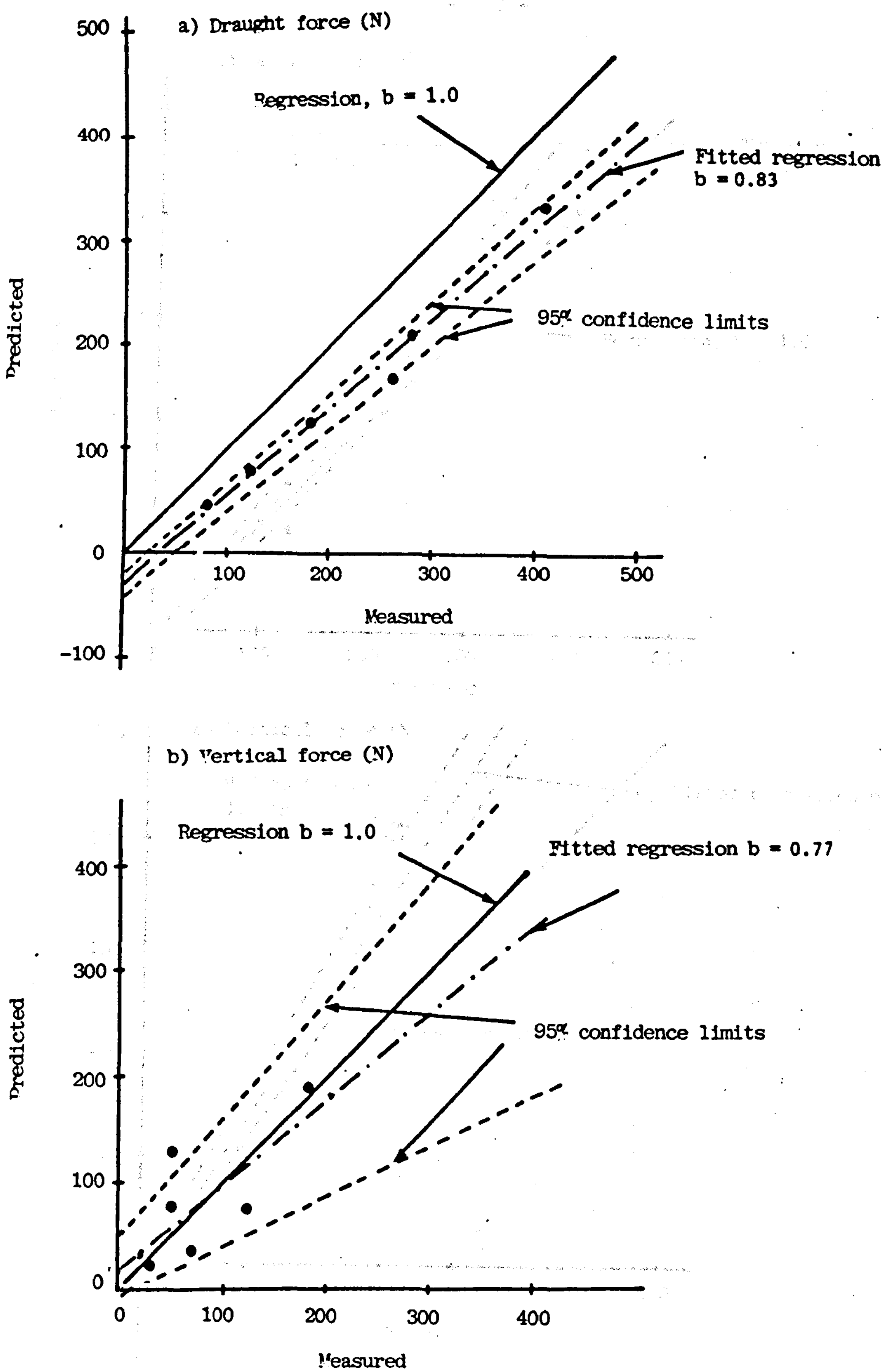


Figure 6.13 Goodness of fit between predicted and measured forces (tine rake angle = 45^{o}, moisture content = 56% dry basis)

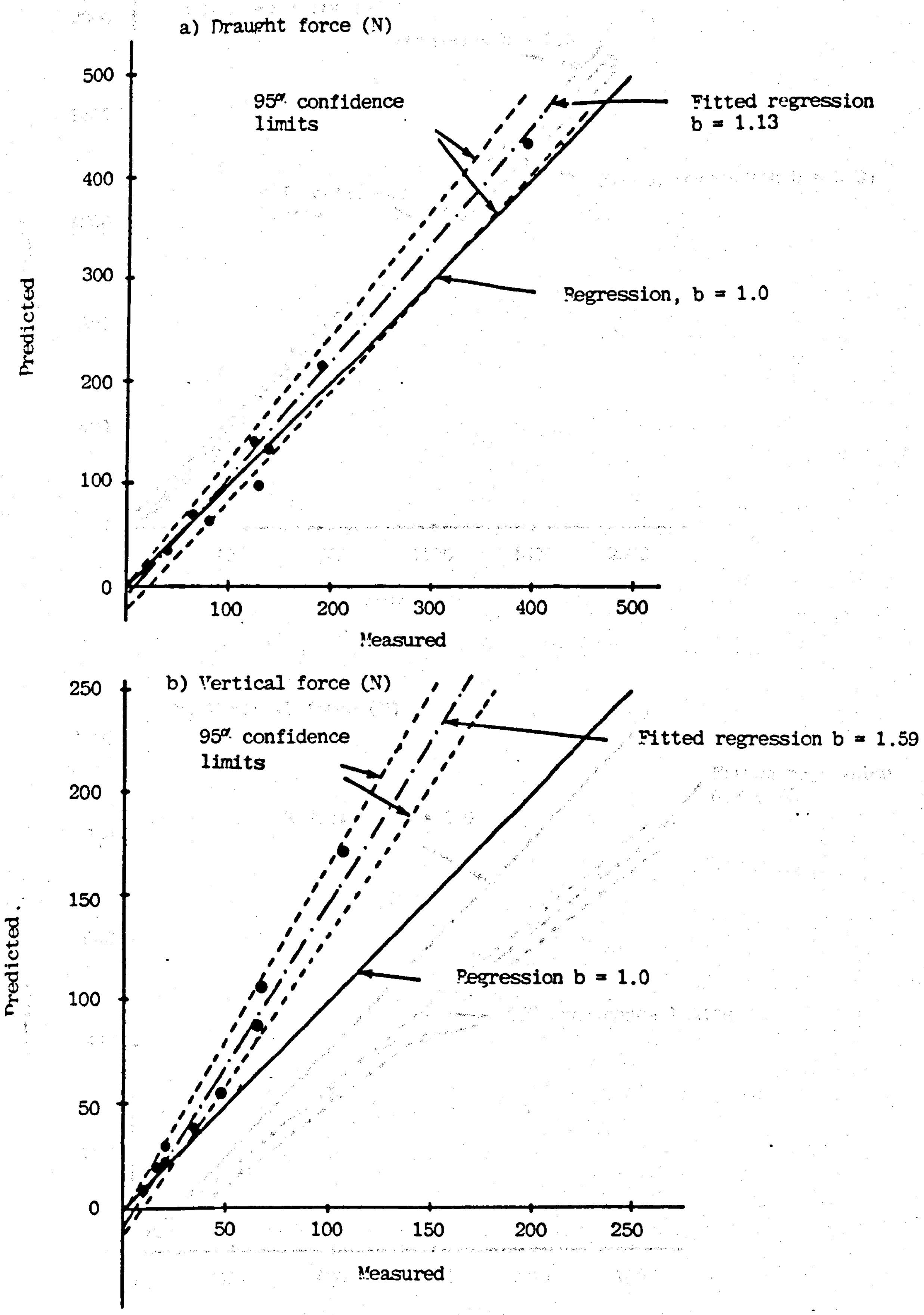


Figure 6.14 Goodness of fit between predicted and measured forces (tine rake angle = 90°, moisture content = 70% dry basis).

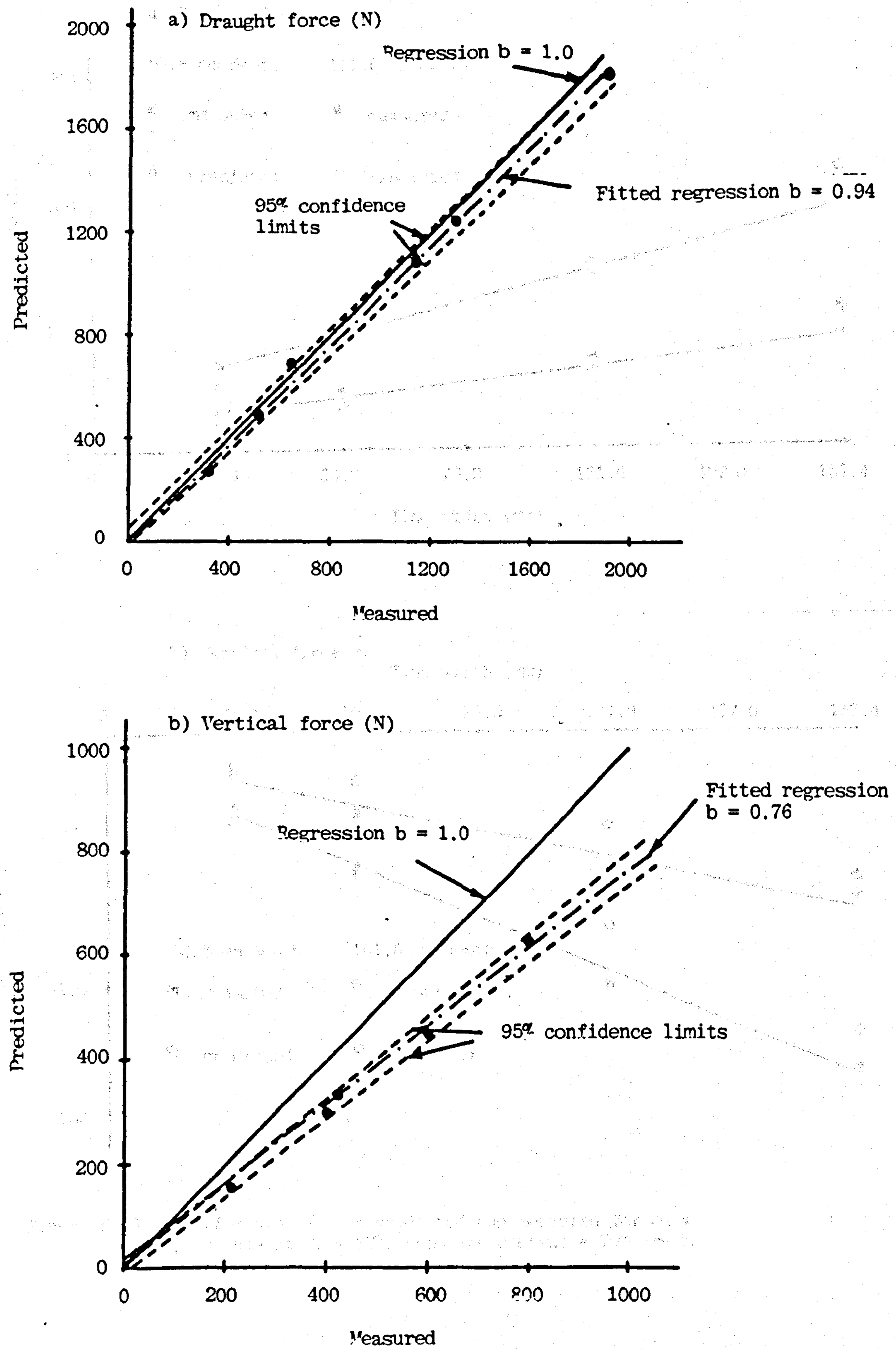
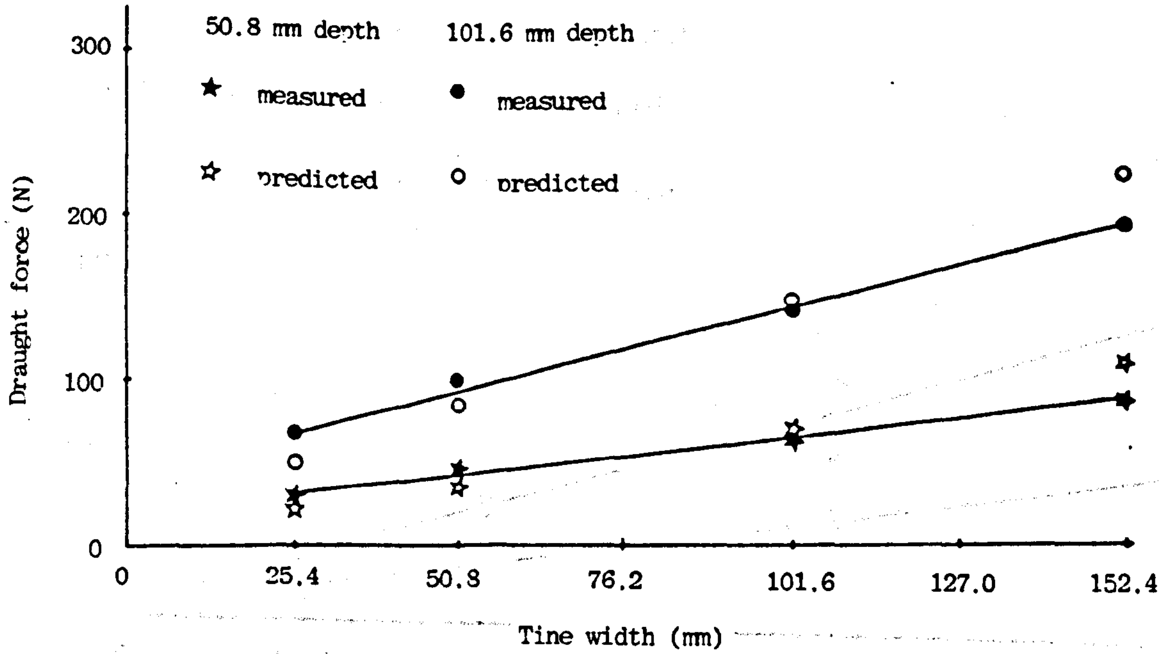


Figure 6.15 Goodness of fit between predicted and measured forces (tine rake angle = 135°, moisture content = 42% dry basis).

a) Draught force



b) Vertical force

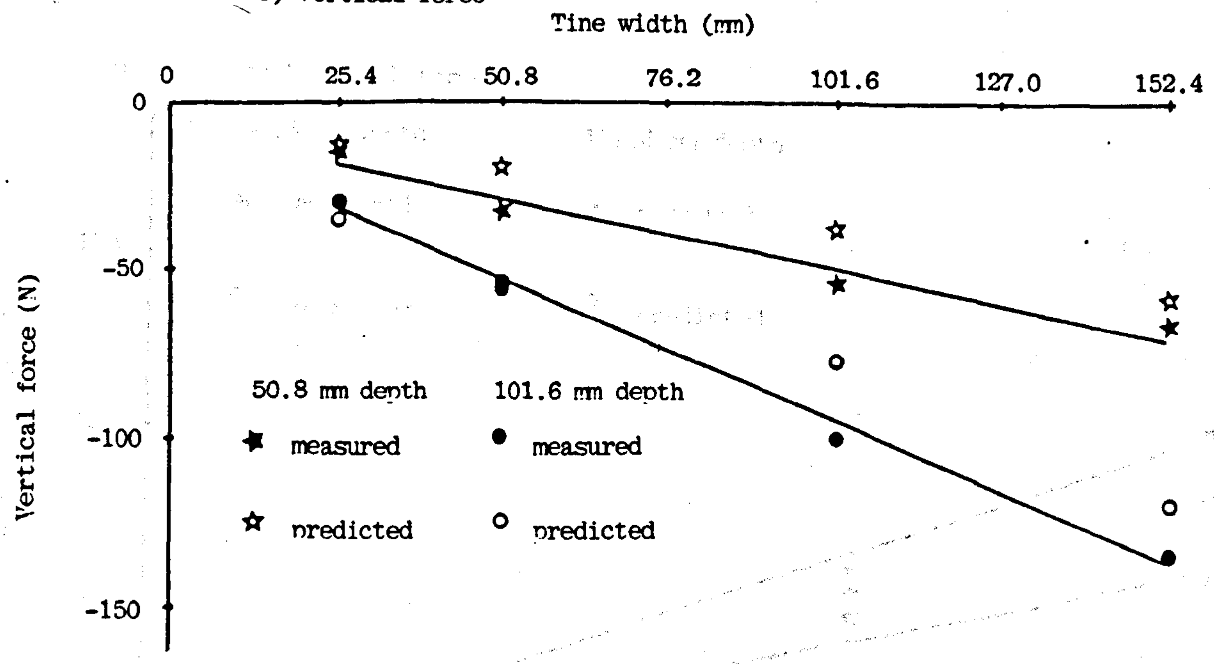
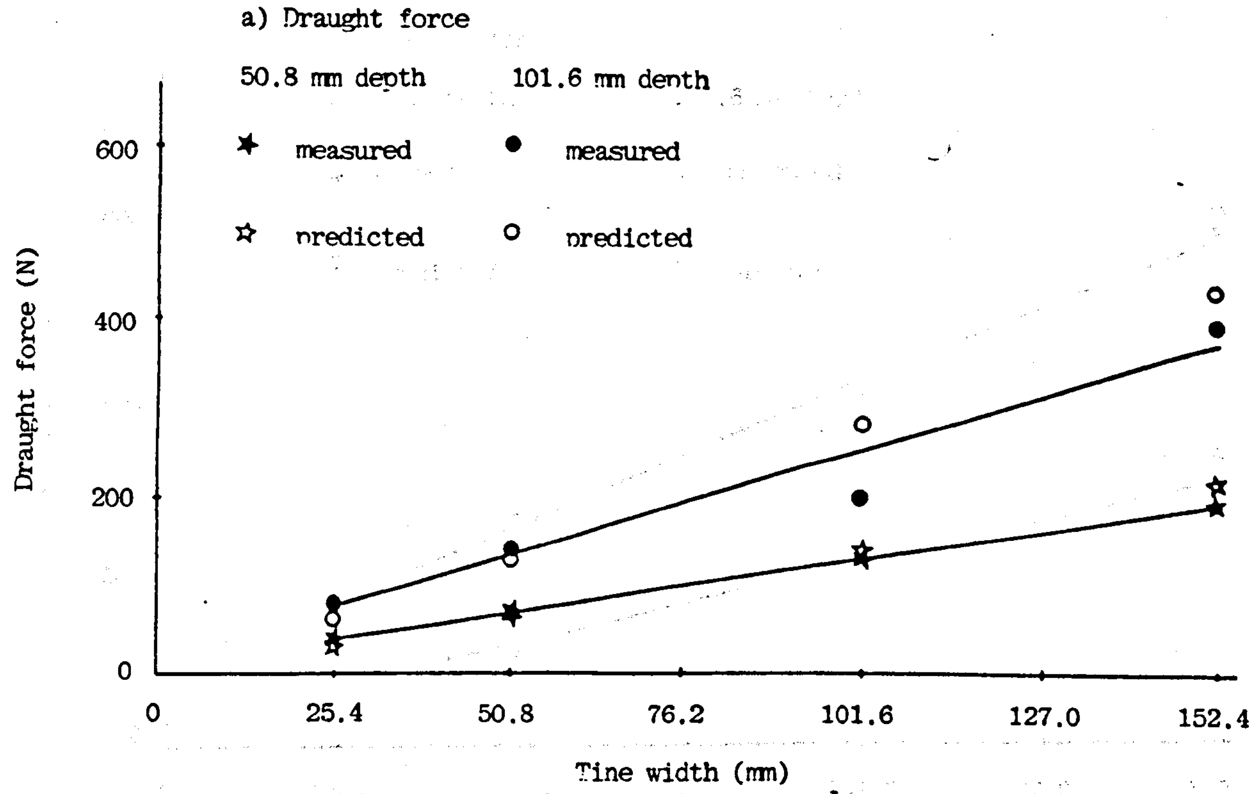


Figure 6.16 Relationship between predicted and measured forces with tine width (Tine rake angle = 45°, moisture content = 70% dry basis).



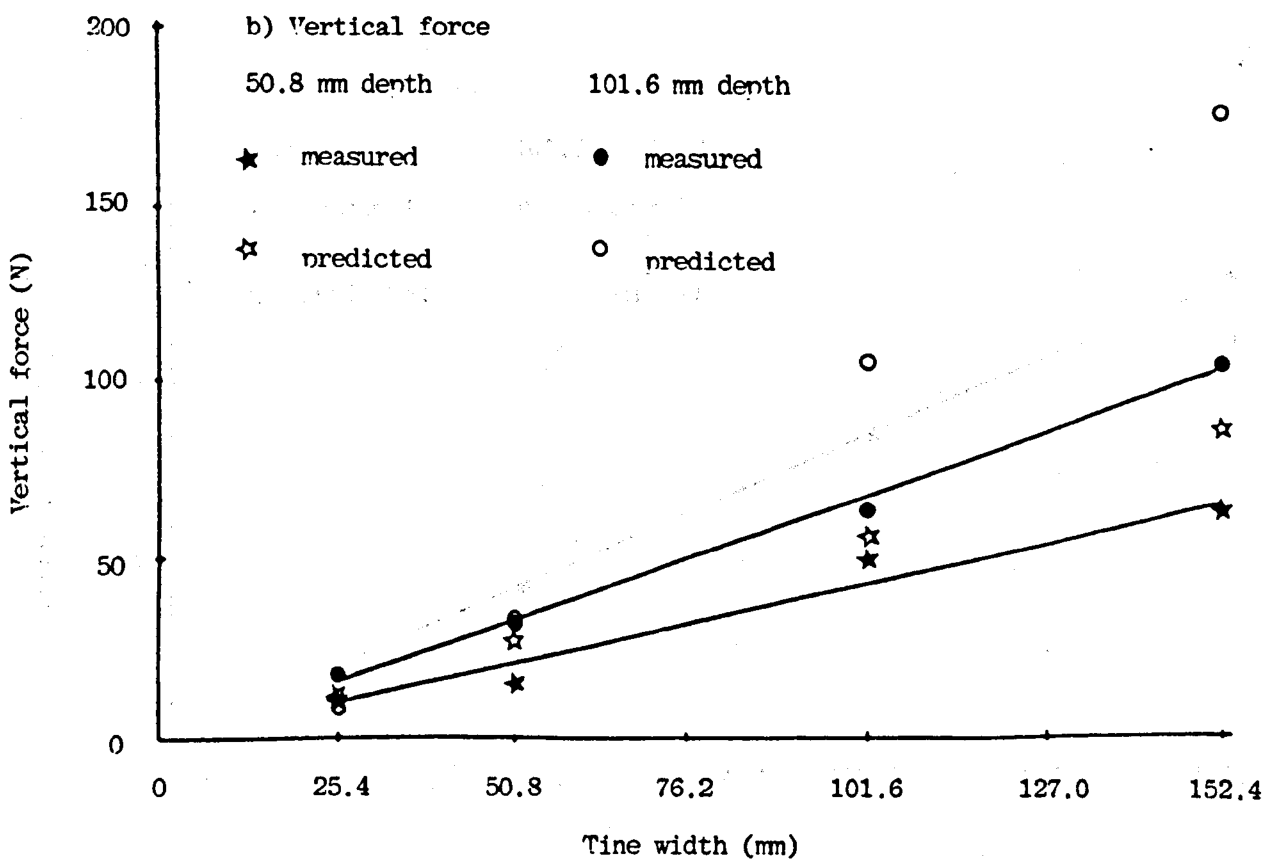


Figure 6.17 Relationship between predicted and measured forces with tine width (Tine rake angle = 90°, moisture content = 70% dry basis).

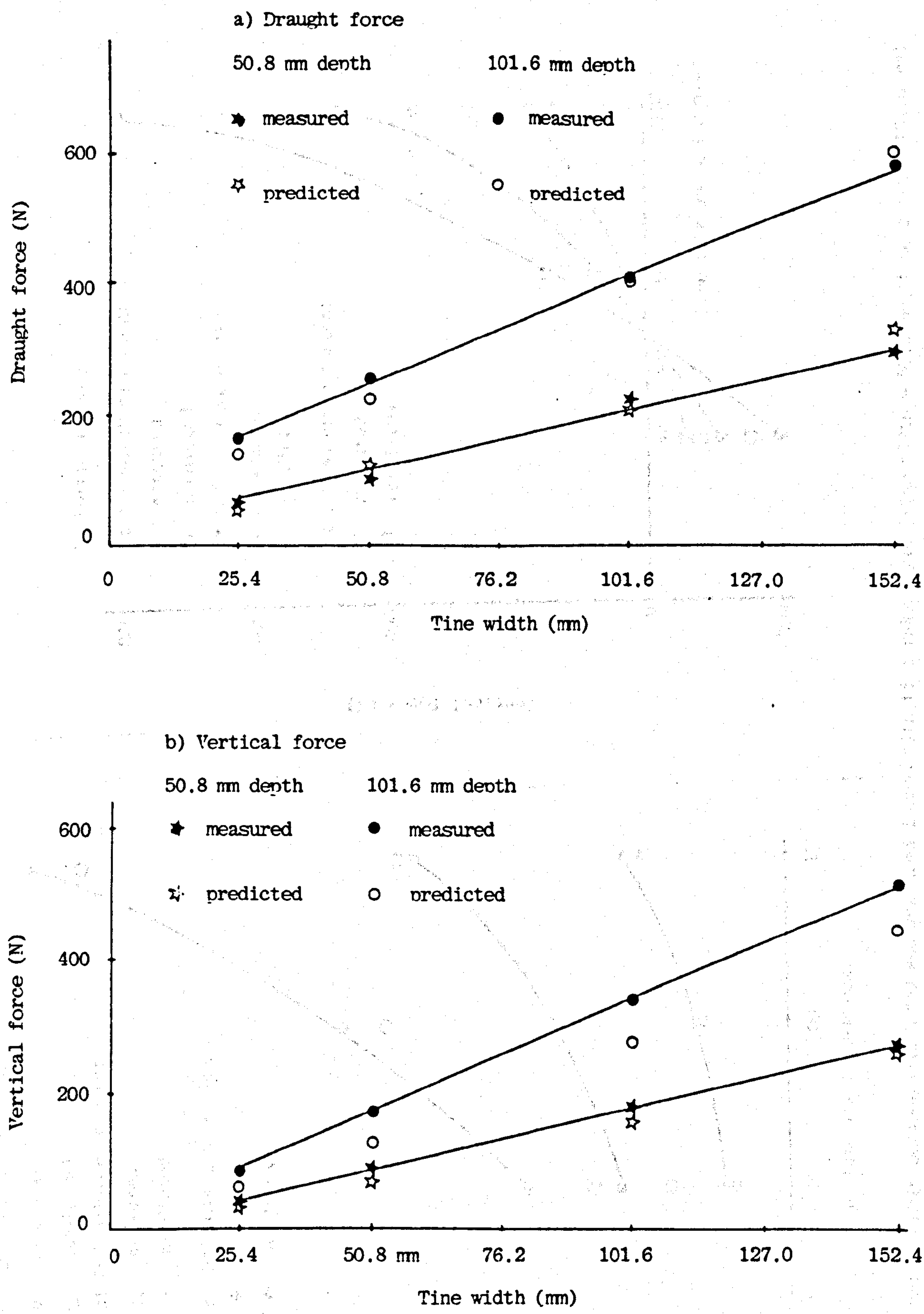


Figure 6.18 Relationship between predicted and measured forces with tine width. (Tine rake angle = 135°, moisture content = 70% dry basis).

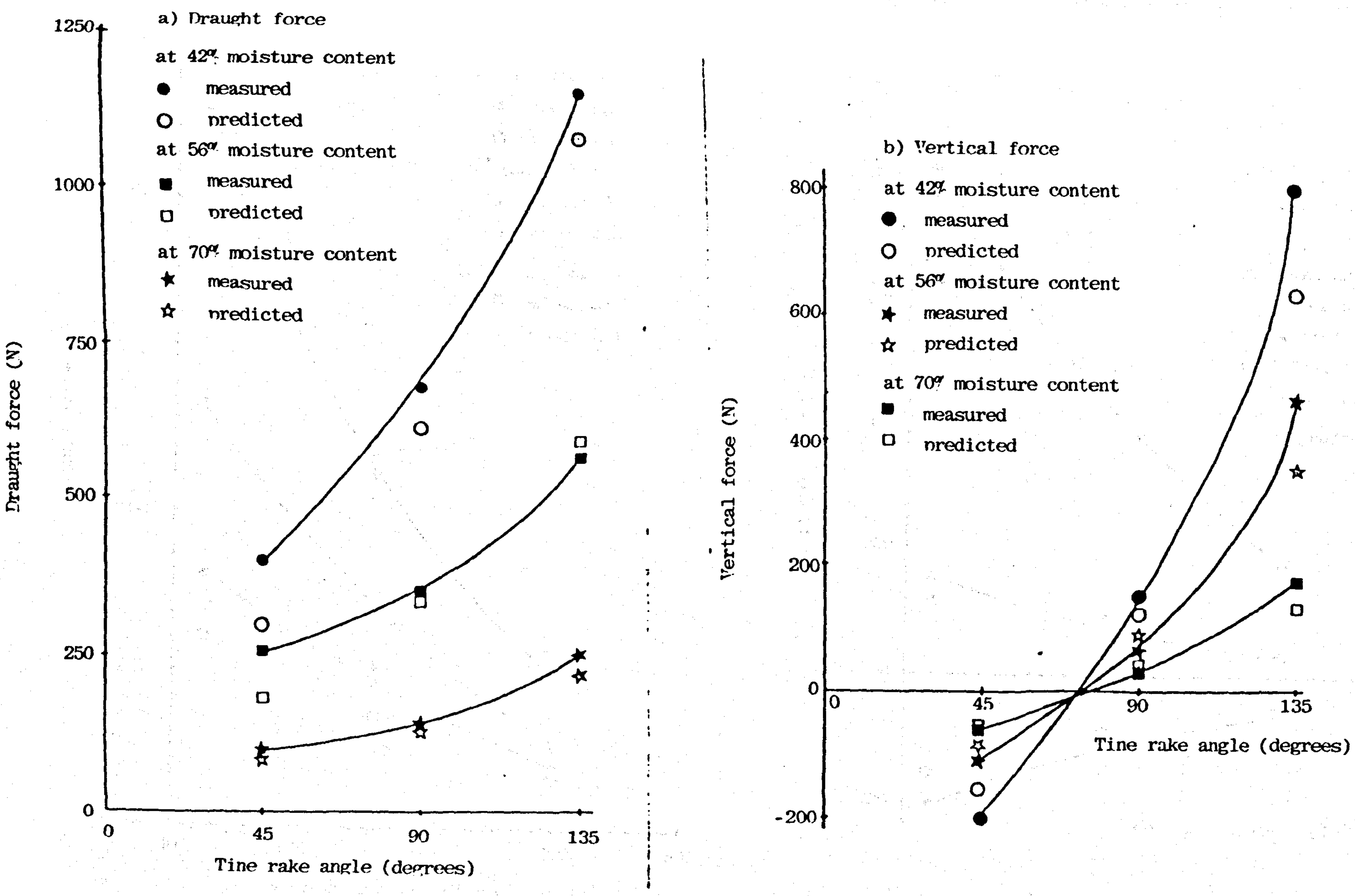


Figure 6.19 Relationship between predicted and measured forces with tine rake angle (tine width = 50.8 mm, tine depth = 101.6 mm)

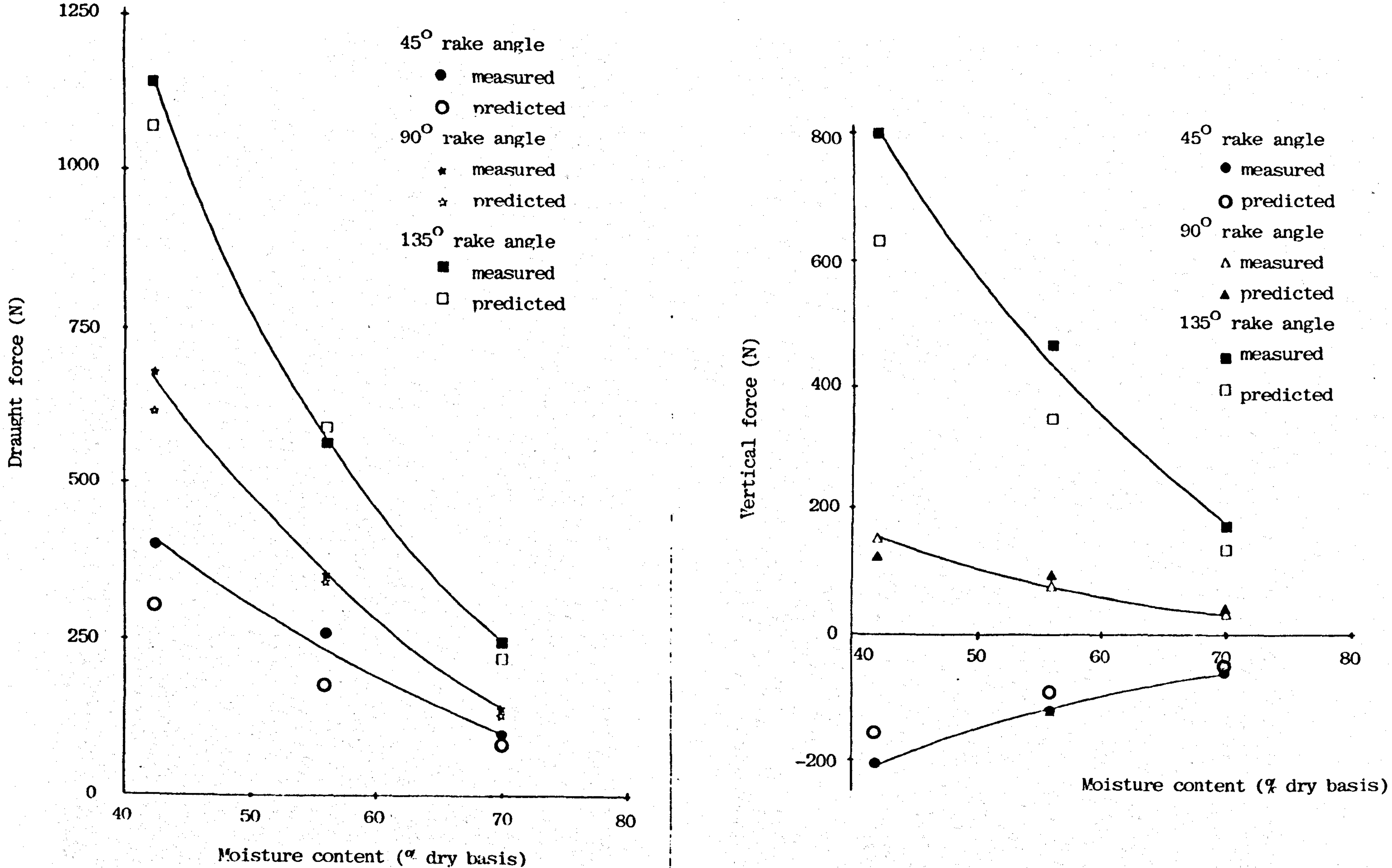


Figure 6.20 Relationship between predicted and measured forces with moisture content (Tine width = 50.8 mm, tine depth = 101.6 mm)

Plate 4.1 A Pugmill

Plate 4.2 Extrusion of soil sample using a hydraulic jack.

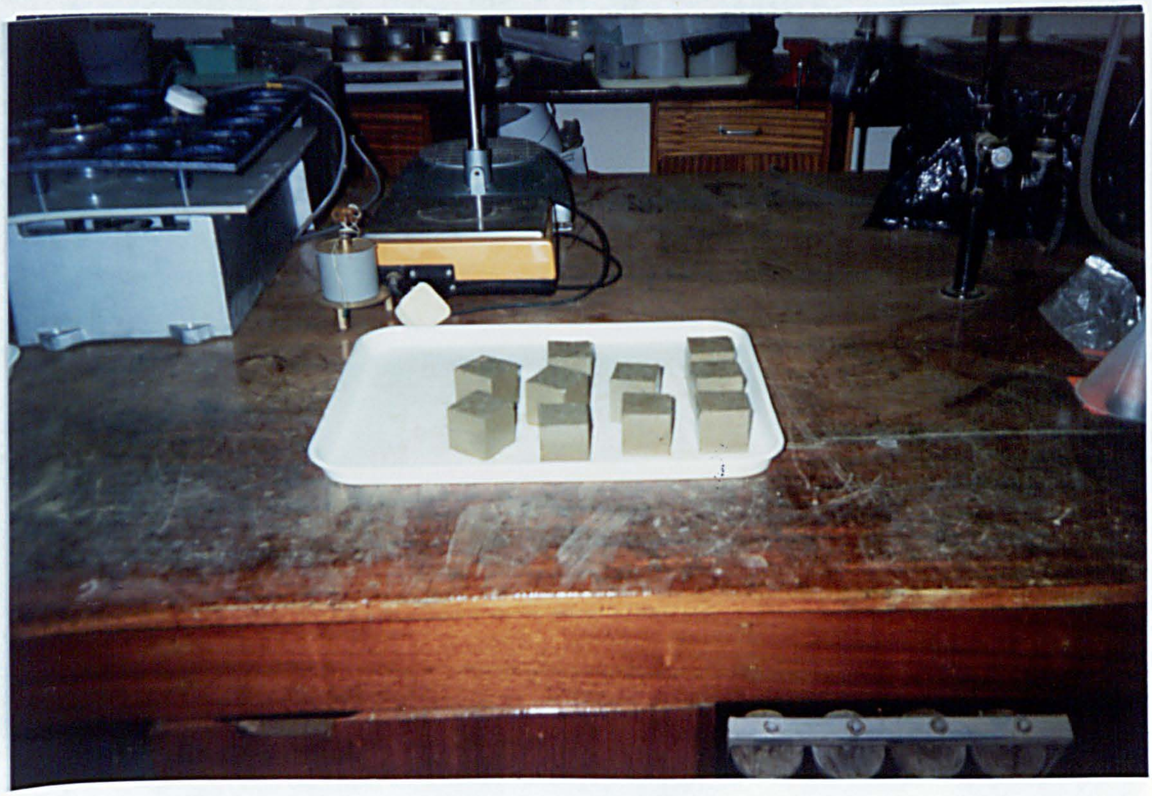


Plate 4.3 Prepared clods (medium size).

Plate 4.4 Protection of clods against moisture loss.

Plate 4.5 Equipment used in clod preparation.

Plate 4.6 Drying of clods on top of an oven.

Plate 4.7 Wetting of clods on a sand-table.

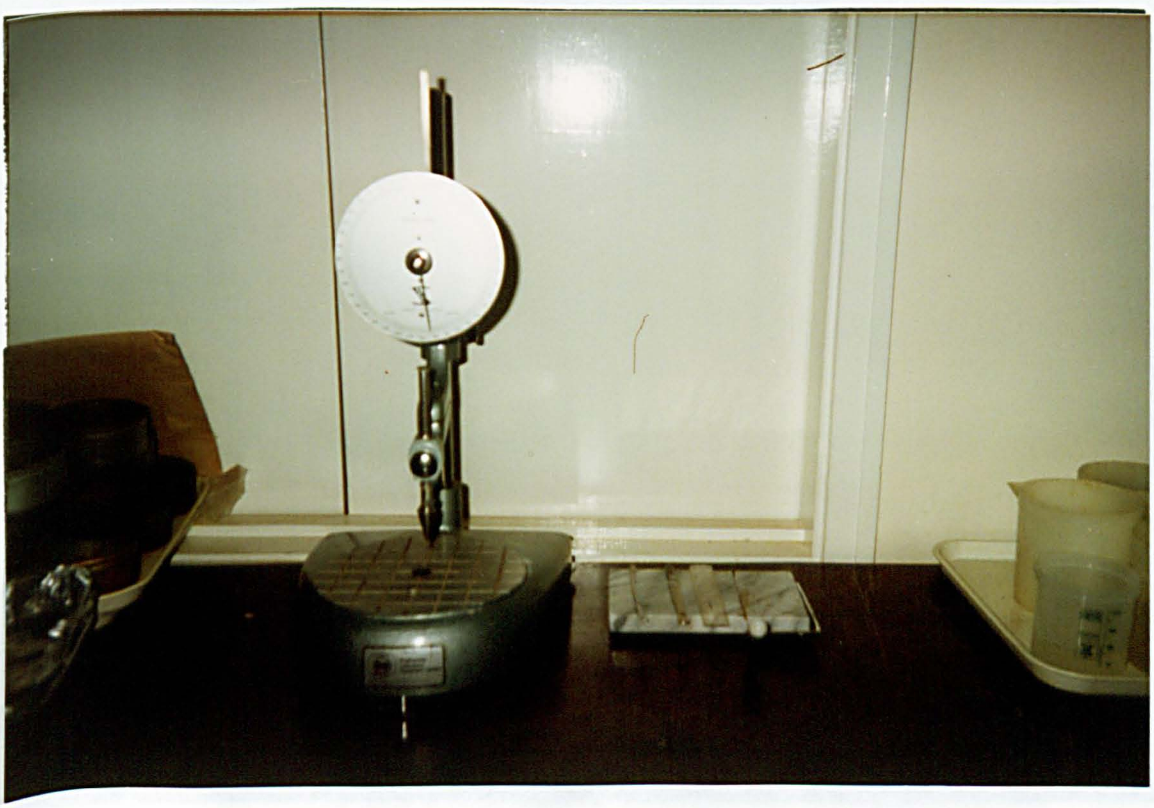


Plate 4.8 Equipment used for measuring clod strength and for slicing clods.

Plate 4.10 A soil leveller.

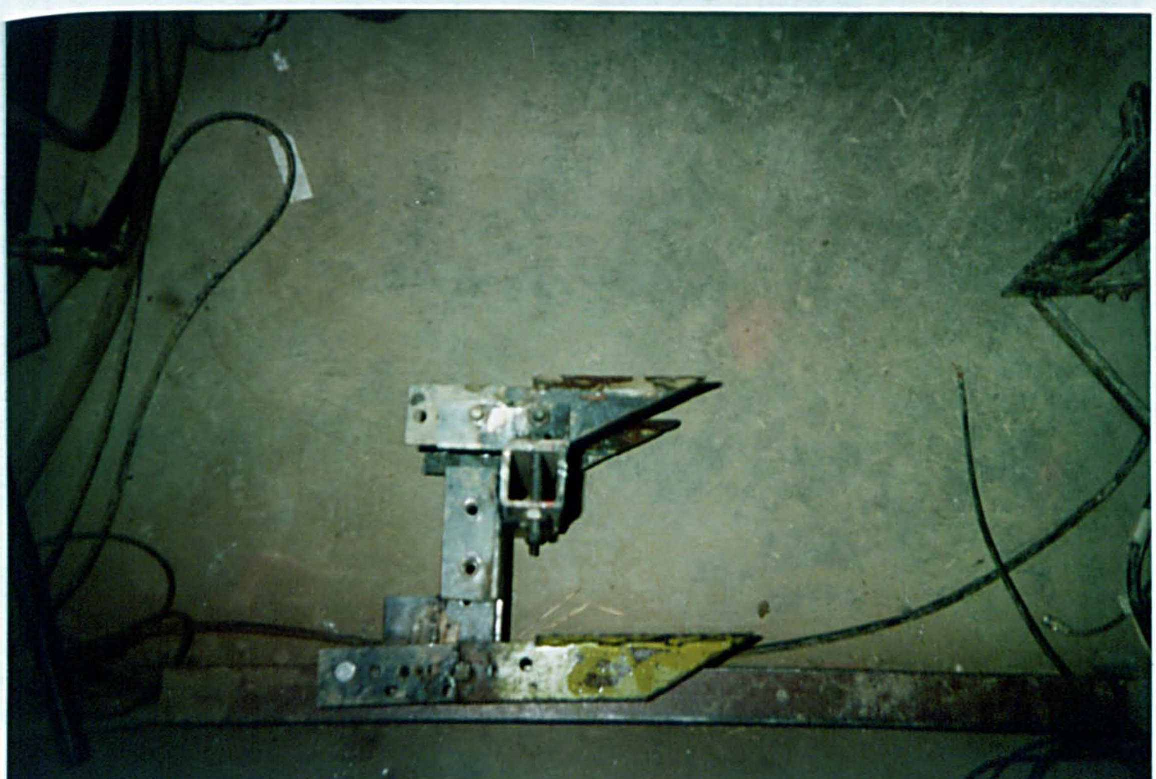


Plate 4.9 A tool holder.

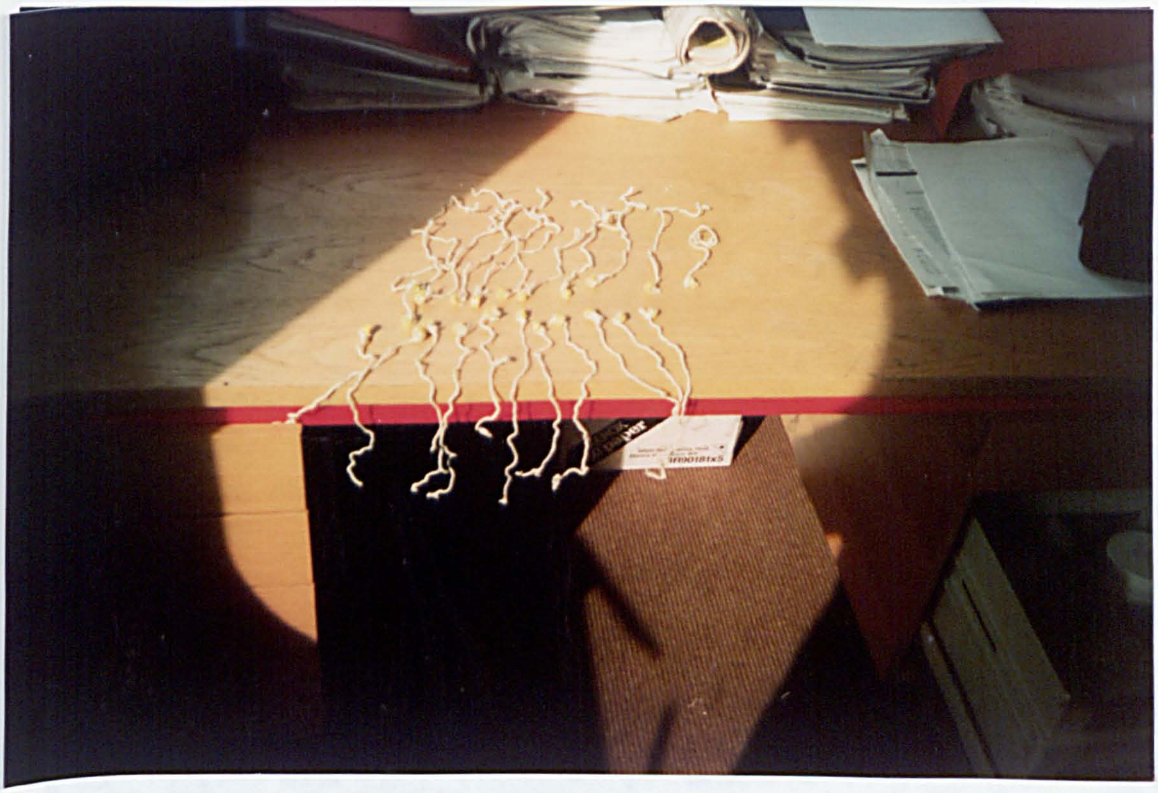


Plate 4.11 Plastic beads with string.

Plate 4.12 Talcum grid on soil surface.

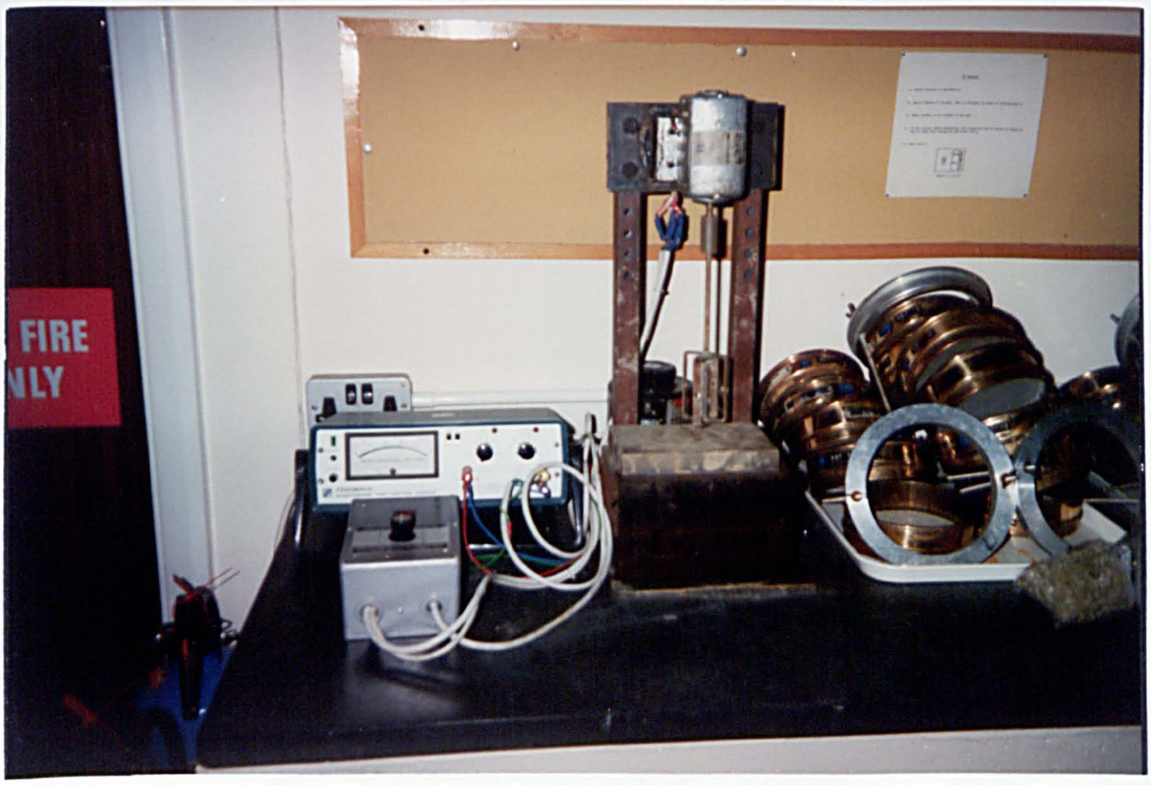


Plate 4.13 A laboratory puddler with instrumentation.

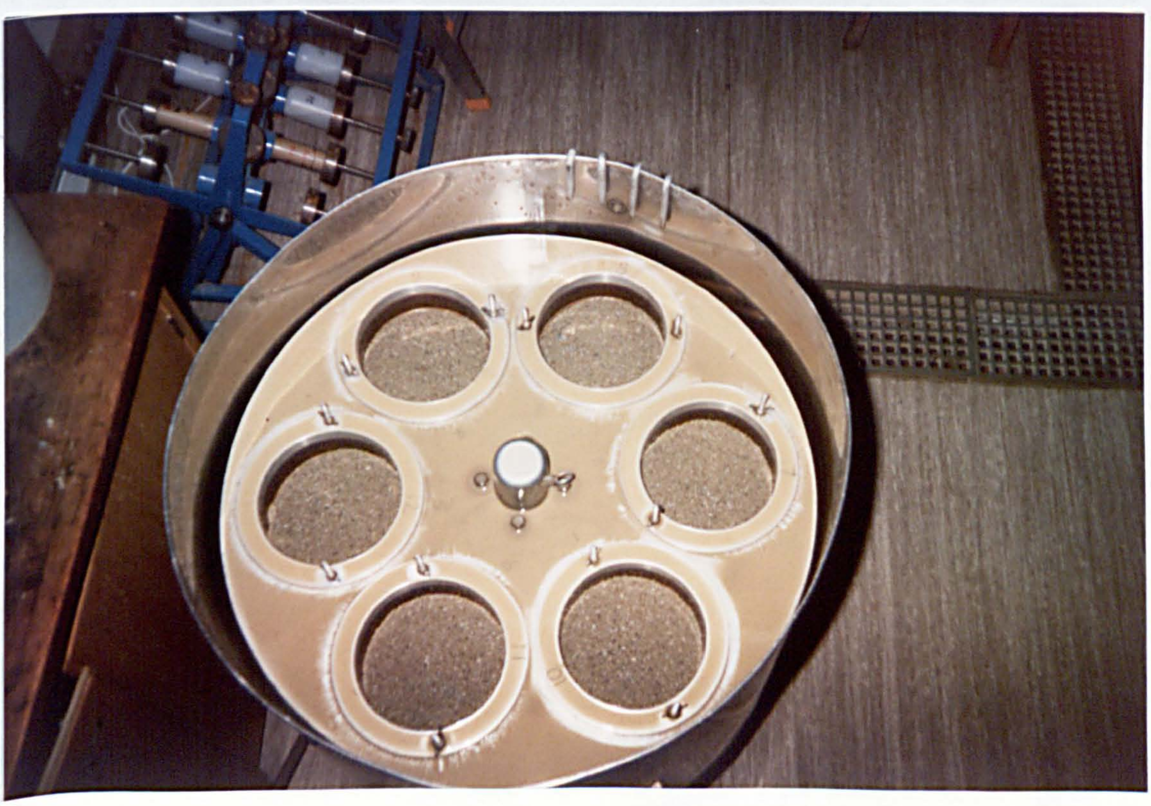


Plate 4.14 A wet sieving apparatus.

Plate 4.15 A set of sieves.

Plate 4.16 Plastic beakers containing puddled soil.

Plate 5.1 Side view of 25.4 mm tine at 45 degree rake angle (depth = 50.8 mm, moisture content = 70% dry basis).

Plate 5.2 Wall of slot cut by a 25.4 mm tine at 152.4 mm depth (moisture content = 70% dry basis).

Plate 5.3 Profile of disturbance by 152.4 mm tine at 45 degree rake angle (depth = 101.6 mm, moisture content = 70% dry basis).

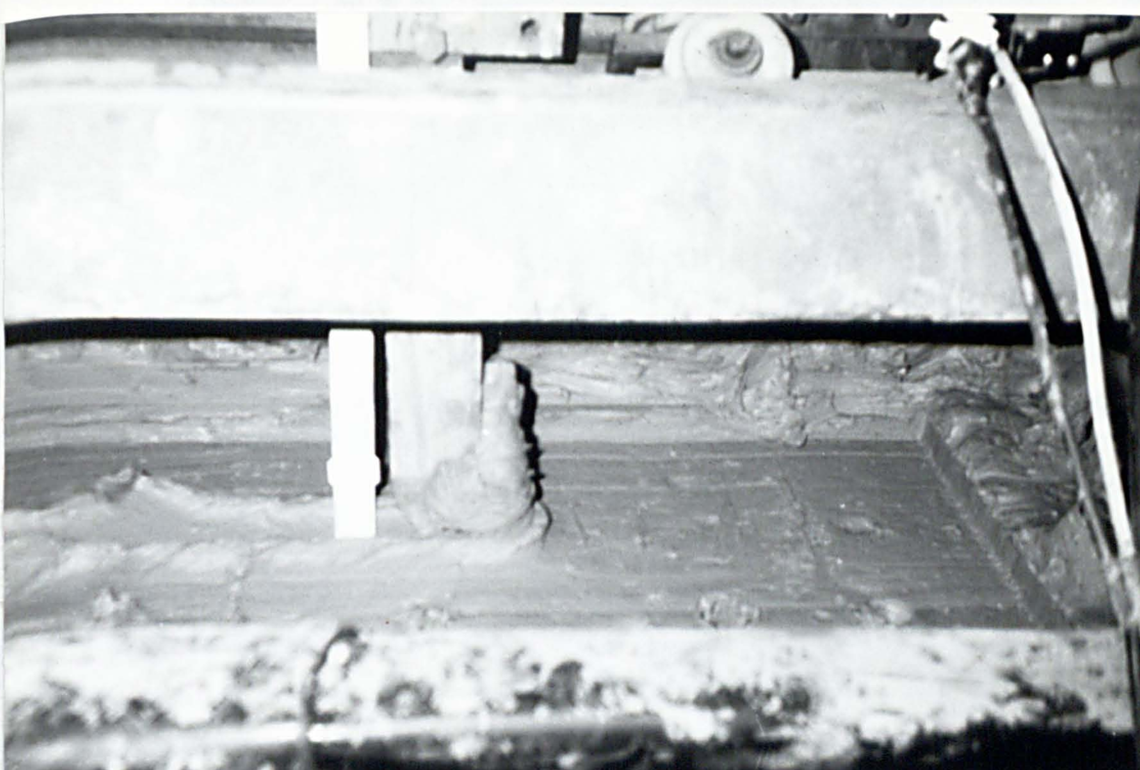


Plate 5.4 Soil movement ahead of a vertical tine (width = 25.4 mm, moisture content = 56% dry basis).

Plate 5.5 Profile of disturbance by a 50.8 mm tine at 42% moisture content (depth = 50.8 mm, rake angle = 90 degrees).

Plate 5.6 Soil movement ahead of a backward raked tine at 152.4 mm depth (width = 50.8 mm, moisture content = 56% dry basis).

Plate 5.7 Profile of disturbance by multiple tines (spacing = 152.4 mm, depth of leading tines = 50.8 mm, moisture content = 56% dry basis).

Plate 5.8 Profile of disturbance by multiple tines (spacing = 152.4 mm, depth of leading tines = 101.6 mm, moisture content = 56% dry basis).

Appendix A.

Detailed Results on Clod, Tine and Soil Puddling Studies.

Table A5.1 Water retention characteristics.

Replicate	Pressure (bars)					
	0	1	2	4	8	15
1	41.65	39.57	37.60	34.68	31.29	28.61
2	42.24	40.64	38.90	36.85	34.99	33.08
3	43.31	40.20	38.15	35.20	31.87	28.86
4	45.49	40.16	37.38	34.19	30.71	28.00
5	44.93	39.43	37.03	34.34	32.12	29.93
6	41.78	34.99	33.55	32.64	29.99	28.11
Mean	43.23	39.17	37.10	34.65	31.83	29.43
sd	1.65	2.09	1.86	1.38	1.73	1.92

Table A5.2 Triaxial test results to determine the values of c and ϕ for a soil density of 1250 kg/m^3 at 42% mosture content.

Sample wt. (g)	σ_3 (kN/m^2)	Max. load (N)	strain %	area mm^2	$\sigma_1 - \sigma_3$ (kN/m^2)	σ_1 (kN/m^2)	q (kN/m^2)	p (kN/m^2)
109.34	6.90	71.95	14.00	1326	54.26	61.16	27.10	34.03
111.07		77.11	10.00	1267	60.86	67.76	30.43	37.33
110.04		66.95	10.00	1267	52.84	59.74	26.42	33.32
		Mean			55.99	62.89	27.99	34.89
108.94	34.50	80.78	14.00	1326	60.92	95.42	30.46	64.96
110.12		86.39	15.00	1334	64.76	99.26	32.38	66.88
106.74		62.27	12.00	1288	48.35	82.85	24.18	58.68
		Mean			58.01	92.51	29.00	63.51
107.76	69.00	89.59	13.00	1303	68.76	137.76	34.38	103.38
105.79		66.15	12.00	1288	51.36	120.36	25.68	94.68
104.77		70.21	13.00	1303	53.88	122.88	26.94	95.94
		Mean			58.00	127.00	29.00	98.00
106.89	103.50	85.49	14.00	1319	64.82	167.82	32.41	135.41
109.41		83.41	14.00	1319	63.24	166.24	31.62	134.62
110.99		69.26	15.00	1334	51.92	154.92	25.96	128.96
		Mean			59.99	162.99	29.99	133.00

Mean sample weight = 108.49 grams

Soil shear strength = 29 kN/m^2

Angle of soil shear strength = 1^0

Soil dry bulk density = 1250 kg/m^3

Table A5.3 Triaxial test results to determine the values of c and ϕ for a soil density of 1000kg/m^3 at 56% moisture content.

Sample wt.(g)	σ_3 (kN/m^2)	Max.load (N)	strain %	area mm^2	$\sigma_1-\sigma_3$ (kN/m^2)	σ_1 (kN/m^2)	q_1 (kN/m^2)	p_1 (kN/m^2)
87.10	6.9	40.00	11.50	1281	31.30	38.20	15.65	22.55
86.90		42.60	12.50	1295	32.92	39.82	16.46	23.36
86.20		43.90	12.00	1288	34.08	40.98	17.04	23.94
		Mean			32.76	39.67	16.35	23.25
89.20	34.50	49.00	12.00	1288	32.00	66.50	16.00	50.50
86.10		49.06	11.50	1281	30.30	64.80	15.15	49.65
87.20		45.36	10.00	1260	36.00	70.50	18.00	52.50
		Mean			32.77	67.30	16.38	50.80
84.90	69.00	41.35	9.50	1253	33.00	102.00	16.50	85.50
85.26		40.95	10.00	1260	32.50	101.50	16.25	85.25
87.80		38.52	7.00	1219	31.60	100.60	15.80	84.80
		Mean			32.37	101.37	16.18	85.18
85.15	103.50	39.62	9.00	1246	31.80	134.80	15.90	118.90
86.19		41.43	8.00	1233	33.60	136.60	16.80	119.80
86.50		43.57	11.00	1274	34.20	137.20	17.10	120.10
		Mean			33.20	136.20	16.60	119.60

Mean sample weight = 86.54 grams

Soil shear strength = 16 kN/m^2

Angle of soil shear strength = 0^0

Soil dry bulk density = 1000 kg/m^3

Table A5.4 Triaxial test results to determine the values of c and ϕ for a soil density of 940 kg/m^3 at 70% moisture content.

Sample wt.(g)	σ_3 (kN/m^2)	Max.load (N)	strain %	area mm^2	$\sigma_1 - \sigma_3$ (kN/m^2)	σ_1 (kN/m^2)	q_1 (kN/m^2)	pl (kN/m^2)
94.72	6.9	14.18	4.8	1202	11.80	18.70	5.90	12.80
93.6		14.59	4.0	1196	12.20	19.10	6.10	13.00
95.10		13.20	3.2	1176	11.22	18.12	5.61	12.51
		Mean			11.74	18.64	5.87	12.77
93.90	34.5	14.41	2.0	1162	12.40	46.9	6.20	40.70
94.80		14.09	2.8	1174	12.00	46.50	6.00	40.50
96.20		13.91	3.2	1179	11.80	46.30	5.90	40.40
		Mean			12.07	46.60	6.03	40.50
93.00	69.00	14.18	2.0	1162	12.20	81.20	6.10	75.10
94.81		13.52	2.8	1174	11.52	80.50	5.76	74.76
95.80		14.26	4.0	1196	11.92	80.92	5.96	74.96
		Mean			11.88	80.87	5.94	74.94
94.70	103.50	13.55	2.4	1168	11.60	115.10	5.80	109.30
93.60		14.62	3.2	1179	12.40	115.90	6.20	109.70
95.20		14.93	3.6	1185	12.60	116.10	6.30	109.80
		Mean			12.60	115.70	6.10	109.60

Mean sample weight = 94.59 grams.

Soil shear strength = 6 kN/m^2 .

Angle of soil shear strength = 0^0.

Soil dry bulk density = 940 kg/m^3 .

Table A5.5 Slider test results to determine the values of c_a and δ for a soil density of 1250 kg/m^3 at 42% moisture content.

Added weight (grams)	Block	Normal stress (kN/m^2)	Tangential stress (kN/m^2)
0	1	0.10	0.30
	2		0.50
	3		0.45
	4		0.35
	5		0.55
	6		0.25
	mean		0.40
250	1	0.26	0.60
	2		0.80
	3		0.95
	4		0.50
	5		0.65
	6		0.40
	mean		0.65
500	1	0.42	0.60
	2		1.10
	3		1.05
	4		1.00
	5		0.80
	6		0.85
	mean		0.90
750	1	0.58	1.45
	2		1.10
	3		0.90
	4		1.25
	5		1.00
	6		1.20
	mean		1.15
1000	1	0.74	1.25
	2		1.30
	3		1.50
	4		1.40
	5		1.20
	6		1.45
	mean		1.35

1250	1	0.90	1.40
	2		1.65
	3		1.85
	4		1.90
	5		1.30
	6		1.50
	mean		1.60

weight of plate = 165.36 grams

area of plate = 155 cm^2

soil-metal shearing resistance = 0.20 kN/m^2

angle of soil-metal shearing resistance = 18^0.

Table A5.6 Slider test results to determine the values of c_a and δ for a soil density of 1000 kg/m^3 at 56% moisture content.

Added weight (grams)	Block	Normal stress (kN/m^2)	Tangential stress (kN/m^2)
0	1	0.10	1.30
	2		1.05
	3		.95
	4		1.25
	5		1.15
	6		0.90
	mean		1.10
250	1	0.26	1.20
	2		1.30
	3		1.70
	4		1.60
	5		1.25
	6		1.35
	mean		1.40
500	1	0.42	1.60
	2		1.65
	3		1.95
	4		1.80
	5		1.90
	6		1.55
	mean		1.75
750	1	0.58	1.82
	2		2.10
	3		2.08
	4		1.80
	5		2.25
	6		1.95
	mean		2.00
1000	1	0.74	2.20
	2		2.55
	3		2.45
	4		2.60
	5		2.30
	6		2.10
	mean		2.40

1250	1	0.90	2.64
	2		2.80
	3		2.66
	4		2.45
	5		2.90
	6		2.75
	mean		2.70

Weight of plate = 165.36 grams

area of plate = 155 cm^2

soil-metal shearing resistance = 0.9 kN/m^2

angle of soil-metal shearing resistance = 22^0

Table A5.7 Slider test results to determine the values of c_a and δ for a soil density of 940 kg/m^3 at 70% moisture content.

Added weight (grams)	Block	Normal stress (kN/m^2)	Tangential stress (kN/m^2)
	1	0.10	1.50
0	2		1.40
	3		1.20
	4		1.55
	5		1.26
	6		1.30
	mean		1.37
	1	0.26	1.70
250	2		1.45
	3		1.55
	4		1.62
	5		1.76
	6		1.36
	mean		1.56
	1	0.42	1.37
500	2		2.15
	3		2.00
	4		1.98
	5		1.74
	6		1.80
	mean		1.84
	1	0.58	2.00
750	2		2.10
	3		2.50
	4		1.90
	5		2.30
	6		2.40
	mean		2.20
	1	0.74	2.30
1000	2		2.80
	3		2.40
	4		2.60
	5		2.20
	6		2.70
	mean		2.50

	1	0.90	2.52
1250	2		2.95
	3		3.05
	4		2.64
	5		2.74
	6		3.14
	mean		2.84

Weight of plate = 165.36 grams

area of plate = 155 cm^2

soil-metal shearing resistance = 1.14 kN/m^2

angle of soil-metal shearing resistance = 20^0

Table A5.8 Volume of unconfined clods after different wetting times (cm^3). Initial moisture content = 12.74% (dry basis).

a) small clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	12.38	12.86	12.22	12.49
1	14.51	15.06	14.31	14.63
3	16.99	16.25	16.49	16.58
5	16.91	16.47	18.20	17.19
7	17.28	17.20	17.01	17.16
14	17.98	18.87	16.05	17.63
21	16.44	17.54	17.32	17.10
28	18.32	16.78	17.89	17.66
35	17.98	18.01	18.89	18.29
42	18.60	18.52	18.15	18.42

b) Medium clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	72.26	75.06	71.32	72.90
1	77.75	80.69	76.68	78.39
3	91.03	87.06	88.35	88.83
5	89.35	92.50	107.83	96.54
7	103.03	102.55	101.42	102.31
14	100.81	105.80	89.99	98.85
21	88.70	100.39	101.20	96.76
28	102.81	100.40	94.17	99.11
35	103.51	103.68	108.74	105.29
42	100.40	105.37	92.58	99.43

c) Large clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	205.64	213.62	202.99	207.47
1	231.23	239.99	228.04	233.14
3	277.27	265.19	269.11	270.58
5	253.12	282.03	285.46	273.48
7	284.28	282.97	279.90	282.37
14	292.46	296.94	271.07	286.77
21	279.42	298.12	294.38	290.64
28	296.80	287.81	290.06	292.31
35	303.00	291.61	298.45	296.17
42	297.79	302.78	300.78	300.45

Table A5.9 Volume of unconfined clods after different wetting times (cm^3) Initial moisture content = 21.76% (dry basis).

a) small clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	14.23	13.93	14.04	14.07
1	15.46	15.12	14.55	15.04
3	15.27	15.61	15.20	15.36
5	15.68	15.94	15.17	15.60
7	15.50	16.20	15.15	15.62
14	17.59	17.46	16.97	17.34
21	17.61	17.23	16.83	17.22
28	17.90	17.70	17.84	17.81
35	18.04	18.99	16.22	17.75
42	18.04	17.51	17.80	17.78

b) Medium clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	79.60	77.70	78.40	78.59
1	84.89	82.81	79.31	82.32
3	85.62	87.75	85.18	86.18
5	89.92	80.09	81.39	83.82
7	87.68	91.75	85.16	88.11
14	91.65	90.90	88.07	90.21
21	90.24	89.32	89.65	89.74
28	91.19	89.93	90.08	90.38
35	86.87	91.97	77.09	85.31
42	92.16	90.95	96.03	93.03

c) Large clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	232.76	227.85	229.65	230.14
1	249.10	243.62	234.43	242.33
3	244.74	250.19	243.62	246.18
5	267.37	241.06	244.54	251.04
7	257.43	269.05	251.61	259.42
14	263.78	261.83	254.48	260.03
21	270.84	264.99	258.84	264.84
28	267.36	265.83	265.02	266.02
35	269.71	283.91	242.49	265.37
42	263.83	269.92	271.95	267.89

Table A5.10 Volume of unconfined clods after different wetting times (cm^3) Initial moisture content = 38.81% (dry basis).

a) Small clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	18.66	18.39	18.44	18.33
1	18.02	18.27	18.33	18.21
3	18.62	17.90	17.61	18.04
5	18.20	19.43	18.47	18.69
7	18.66	18.14	17.93	18.24
14	18.36	18.61	18.68	18.55
21	18.19	18.42	18.47	18.36
28	18.75	18.38	18.20	18.44
35	19.09	17.51	18.65	18.42
42	17.89	18.46	18.36	18.24

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	84.37	85.69	85.98	85.35
1	85.43	86.89	87.24	86.54
3	91.26	86.88	85.11	87.73
5	85.99	92.76	86.48	87.69
7	88.30	85.28	84.06	85.86
14	86.07	87.52	87.92	87.17
21	85.02	86.35	86.64	86.00
28	89.15	87.10	86.10	87.43
35	90.65	81.90	88.21	86.94
42	85.00	88.35	87.76	87.06

c) Large clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	288.68	292.33	293.13	291.38
1	282.08	285.99	286.93	285.05
3	305.24	293.43	288.68	295.73
5	283.11	302.24	287.28	290.73
7	295.56	287.33	283.99	288.91
14	291.44	295.41	296.52	294.46
21	286.89	290.53	291.31	289.58
28	294.45	288.71	285.88	289.65
35	294.89	270.48	288.09	284.54
42	285.48	294.58	292.98	291.07

Table A5.11 Dry bulk density of unconfined clods wetted for different times (Mg/m^3). Initial moisture content = 12.74% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.95	1.87	1.96	1.93
1	1.65	1.58	1.66	1.63
3	1.45	1.53	1.41	1.46
5	1.51	1.47	1.26	1.41
7	1.33	1.38	1.37	1.36
14	1.35	1.23	1.49	1.36
21	1.38	1.32	1.34	1.35
28	1.28	1.38	1.36	1.34
35	1.34	1.31	1.25	1.30
42	1.33	1.24	1.34	1.30

b) Medium clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	1.94	1.86	1.95	1.92
1	1.75	1.68	1.76	1.73
3	1.51	1.59	1.47	1.52
5	1.57	1.53	1.31	1.47
7	1.34	1.39	1.38	1.37
14	1.37	1.35	1.41	1.38
21	1.42	1.36	1.38	1.39
28	1.34	1.44	1.36	1.38
35	1.38	1.35	1.29	1.34
42	1.37	1.28	1.38	1.34

c) Large clod

Wetting period (Days)	Sample 1	Sample 2	Sample 3	Mean
0	1.95	1.87	1.96	1.93
1	1.64	1.57	1.65	1.62
3	1.38	1.46	1.34	1.39
5	1.39	1.45	1.34	1.39
7	1.37	1.36	1.41	1.38
14	1.32	1.36	1.30	1.33
21	1.34	1.28	1.30	1.31
28	1.32	1.28	1.29	1.30
35	1.33	1.28	1.31	1.30
42	1.27	1.30	1.30	1.29

Table A5.12 Dry bulk density of unconfined clods wetted for different times (Mg/m^3). Initial moisture content= 21.76% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.54	1.69	1.60	1.61
1	1.53	1.56	1.61	1.57
3	1.52	1.59	1.62	1.58
5	1.37	1.47	1.56	1.47
7	1.47	1.40	1.49	1.45
14	1.42	1.41	1.43	1.42
21	1.34	1.41	1.39	1.38
28	1.40	1.38	1.36	1.38
35	1.33	1.30	1.39	1.34
42	1.36	1.35	1.32	1.34

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.47	1.62	1.53	1.54
1	1.46	1.49	1.54	1.50
3	1.43	1.50	1.53	1.49
5	1.37	1.45	1.55	1.46
7	1.44	1.37	1.46	1.42
14	1.39	1.36	1.39	1.38
21	1.35	1.39	1.36	1.37
28	1.37	1.37	1.34	1.36
35	1.34	1.31	1.40	1.35
42	1.34	1.33	1.30	1.32

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.59	1.74	1.65	1.66
1	1.52	1.55	1.59	1.56
3	1.47	1.54	1.57	1.53
5	1.38	1.48	1.57	1.48
7	1.49	1.42	1.51	1.47
14	1.40	1.43	1.43	1.42
21	1.37	1.44	1.42	1.41
28	1.43	1.39	1.38	1.40
35	1.22	1.29	1.48	1.33
42	1.30	1.33	1.34	1.32

Table A5.13 Dry bulk density of unconfined clods wetted for different times (Mg/m^3). Initial moisture content= 38.81% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.29	1.30	1.28	1.29
1	1.28	1.30	1.31	1.30
3	1.30	1.33	1.31	1.32
5	1.27	1.25	1.33	1.28
7	1.28	1.27	1.35	1.30
14	1.27	1.30	1.30	1.29
21	1.31	1.29	1.29	1.30
28	1.28	1.30	1.31	1.30
35	1.28	1.32	1.31	1.30
42	1.33	1.27	1.31	1.30

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.29	1.30	1.28	1.29
1	1.26	1.28	1.29	1.28
3	1.24	1.26	1.32	1.27
5	1.27	1.25	1.33	1.28
7	1.26	1.25	1.33	1.28
14	1.32	1.29	1.29	1.30
21	1.33	1.31	1.31	1.32
28	1.28	1.33	1.33	1.32
35	1.29	1.33	1.32	1.31
42	1.35	1.29	1.33	1.32

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.29	1.30	1.28	1.29
1	1.25	1.26	1.29	1.27
3	1.33	1.26	1.26	1.28
5	1.27	1.25	1.33	1.28
7	1.25	1.29	1.31	1.28
14	1.29	1.26	1.26	1.27
21	1.29	1.27	1.27	1.28
28	1.26	1.30	1.30	1.29
35	1.29	1.33	1.32	1.30
42	1.30	1.29	1.33	1.31

Table A5.14 Volume of confined clods after different wetting times (cm^3). Initial moisture content = 11.19% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	9.92	9.97	9.79	9.89
1	14.47	14.64	13.11	14.08
2	14.08	13.93	13.71	13.91
3	14.61	14.30	14.83	14.58
4	13.52	14.11	14.78	14.14
5	13.25	14.67	14.20	14.04
6	14.48	13.21	14.09	13.93
7	14.65	15.00	14.47	14.71

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	57.90	58.27	59.56	58.58
1	75.60	78.35	79.27	77.74
2	85.47	83.13	82.28	83.63
3	81.32	80.35	81.03	80.90
4	75.85	81.60	81.58	79.68
5	79.40	79.91	79.73	79.68
6	82.30	82.26	81.77	82.11
7	82.38	83.49	81.83	82.57

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	200.56	200.72	198.33	199.87
1	238.46	238.65	235.81	237.64
2	252.51	252.71	249.70	251.64
3	274.69	274.90	271.64	273.74
4	274.21	274.43	271.17	273.27
5	279.01	279.23	275.91	278.05
6	281.97	282.19	278.84	281.00
7	280.36	280.58	277.25	279.40

Table A5.15 Volume of confined clods after different wetting times (cm^3). Initial moisture content = 21.31% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	10.31	10.73	10.89	10.31
1	13.01	13.17	13.21	13.13
2	13.44	13.36	13.54	13.45
3	13.75	13.11	13.10	13.32
4	13.11	13.40	13.55	13.35
5	13.24	13.46	13.25	13.32
6	13.57	13.29	13.46	13.44
7	13.66	13.20	13.49	13.45

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	67.58	66.47	66.69	66.91
1	73.84	76.44	75.54	75.27
2	79.85	78.66	75.29	77.93
3	80.18	79.70	80.37	80.08
4	81.12	83.02	80.37	81.50
5	81.76	81.72	80.49	81.32
6	79.51	80.80	80.98	80.43
7	80.45	81.87	81.39	81.24

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	220.52	223.27	221.28	221.69
1	227.19	230.02	227.93	228.38
2	237.04	234.37	240.32	237.24
3	241.26	244.27	242.05	242.53
4	250.76	253.89	251.58	252.08
5	255.89	259.08	256.73	257.23
6	269.46	272.82	270.34	270.87
7	280.36	281.97	281.28	281.20

Table A5.16 Volume of confined clods after different wetting times (cm^3). Initial moisture content = 37.57% (dry basis)

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	14.18	14.17	14.02	14.12
1	13.72	13.36	13.62	13.57
2	13.93	13.80	14.04	13.92
3	13.72	13.94	14.05	13.90
4	13.81	13.89	13.86	13.85
5	13.98	14.20	14.26	14.15
6	14.22	13.80	14.06	14.03
7	14.02	13.78	14.23	14.01

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	82.99	82.47	82.52	82.66
1	81.11	81.16	81.36	81.21
2	81.37	81.43	80.39	81.06
3	80.92	81.18	81.89	81.33
4	80.48	81.24	81.22	80.98
5	81.60	81.93	80.70	81.41
6	82.25	83.07	81.91	82.41
7	81.70	81.74	81.36	81.60

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	273.50	275.95	276.22	275.22
1	272.47	274.91	275.18	274.19
2	273.50	275.95	276.22	275.22
3	276.94	279.42	279.69	278.68
4	276.05	278.52	278.80	277.79
5	278.27	280.76	281.04	280.02
6	278.32	280.81	281.09	280.07
7	278.27	280.76	281.04	280.02

Table A5.17 Dry bulk density of confined clods after different wetting times (Mg/m^3). Initial moisture content = 11.19% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.73	1.86	1.83	1.81
1	1.28	1.24	1.32	1.28
2	1.27	1.25	1.28	1.27
3	1.24	1.28	1.27	1.26
4	1.27	1.30	1.26	1.28
5	1.30	1.25	1.26	1.27
6	1.27	1.32	1.33	1.31
7	1.30	1.31	1.26	1.29

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.73	1.92	1.82	1.83
1	1.39	1.35	1.34	1.36
2	1.26	1.29	1.30	1.28
3	1.30	1.31	1.29	1.30
4	1.33	1.34	1.28	1.32
5	1.32	1.34	1.34	1.33
6	1.28	1.29	1.30	1.29
7	1.28	1.27	1.32	1.29

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.76	1.79	1.81	1.79
1	1.50	1.53	1.54	1.52
2	1.42	1.43	1.44	1.43
3	1.30	1.33	1.34	1.32
4	1.28	1.32	1.33	1.31
5	1.28	1.29	1.33	1.30
6	1.28	1.28	1.31	1.29
7	1.27	1.28	1.32	1.29

Table A5.18 Dry bulk density of confined clods after different wetting times (Mg/m^3). Initial moisture content = 21.31% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.77	1.67	1.64	1.69
1	1.41	1.35	1.39	1.38
2	1.31	1.36	1.35	1.34
3	1.33	1.38	1.39	1.37
4	1.35	1.35	1.38	1.36
5	1.37	1.33	1.34	1.35
6	1.31	1.36	1.37	1.35
7	1.29	1.34	1.33	1.32

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.63	1.57	1.61	1.60
1	1.43	1.42	1.38	1.41
2	1.35	1.36	1.42	1.38
3	1.34	1.31	1.30	1.32
4	1.28	1.27	1.32	1.29
5	1.29	1.33	1.34	1.32
6	1.30	1.34	1.31	1.32
7	1.34	1.30	1.29	1.31

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.60	1.64	1.63	1.62
1	1.56	1.60	1.59	1.58
2	1.52	1.53	1.49	1.51
3	1.46	1.50	1.49	1.48
4	1.40	1.46	1.44	1.43
5	1.38	1.42	1.41	1.40
6	1.30	1.37	1.36	1.34
7	1.25	1.29	1.28	1.27

Table A5.19 Dry bulk density of confined clods after different wetting times (Mg/m^3). Initial moisture content = 37.57% (dry basis).

a) Small clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.27	1.31	1.29	1.29
1	1.28	1.32	1.31	1.30
2	1.28	1.29	1.32	1.30
3	1.34	1.30	1.31	1.32
4	1.29	1.34	1.30	1.31
5	1.28	1.29	1.32	1.30
6	1.25	1.32	1.27	1.28
7	1.32	1.29	1.28	1.30

b) Medium clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
0	1.27	1.31	1.30	1.29
1	1.30	1.33	1.34	1.32
2	1.29	1.34	1.32	1.32
3	1.33	1.29	1.32	1.31
4	1.30	1.34	1.31	1.32
5	1.29	1.33	1.32	1.31
6	1.28	1.29	1.32	1.30
7	1.30	1.34	1.33	1.32

c) Large clod

Wetting period (days)	Sample 1	Sample 2	Sample 3	Mean
1	1.28	1.31	1.29	1.29
2	1.29	1.30	1.33	1.30
3	1.27	1.29	1.29	1.28
4	1.28	1.26	1.31	1.28
5	1.26	1.29	1.27	1.27
6	1.31	1.27	1.28	1.28
7	1.28	1.30	1.27	1.29

Table A5.20 Moisture content of 0-10 mm layer of unconfined soil clods at different wetting times (percentage dry basis) Initial moisture content = 12.74% (dry basis)

Clod size	Block	Wetting time (days)				
		0	1	3	5	7
Small	1	12.94	31.85	31.69	32.71	31.28
	2	12.33	30.07	28.99	34.21	32.69
	3	12.10	33.93	33.79	31.96	34.26
	mean	12.46	31.95	31.49	32.96	32.75
Medium	1	12.10	29.58	29.68	31.99	35.61
	2	12.85	30.49	31.43	32.95	36.59
	3	12.34	32.13	30.68	32.70	36.88
	mean	12.43	30.73	30.60	32.88	35.36
Large	1	9.36	28.23	34.41	38.62	40.89
	2	9.51	29.65	36.07	37.50	36.65
	3	9.32	27.94	36.07	40.29	37.18
	mean	9.40	28.60	35.67	38.80	38.24
		14	21	28	35	42
Small	1	33.01	36.88	35.66	37.33	38.93
	2	34.87	36.74	35.83	36.16	38.52
	3	35.17	37.16	37.20	36.22	36.83
	mean	34.35	36.93	36.23	36.57	38.09
Medium	1	37.16	38.16	36.80	38.77	37.45
	2	37.56	38.40	37.36	41.35	35.76
	3	35.98	35.82	44.58	40.64	43.41
	mean	36.90	37.13	39.58	40.25	38.87
Large	1	36.97	37.10	36.07	37.58	37.93
	2	37.13	37.82	38.61	38.70	41.07
	3	37.74	40.44	42.20	41.49	42.02
	mean	37.28	38.45	38.96	39.26	40.34

Table A5.21 Moisture content of 0-10 mm layer of unconfined soil clods at different wetting times (percentage dry basis). Initial moisture content = 21.76% (dry basis)

Clod size	Block	Wetting time (days) 0	1	3	5	7
Small	1	20.73	26.00	28.85	31.90	30.32
	2	21.52	26.32	25.67	31.37	35.50
	3	20.12	28.74	27.04	29.37	30.23
	mean	20.79	27.02	27.19	30.88	32.02
Medium	1	19.99	27.96	27.10	28.97	33.68
	2	19.48	26.16	27.94	31.54	30.92
	3	18.84	26.83	28.21	29.82	33.07
	mean	19.44	26.98	27.75	30.11	32.56
Large	1	17.96	27.31	33.40	33.67	39.16
	2	18.26	27.63	32.62	35.63	40.36
	3	17.88	25.81	34.37	36.42	43.54
	mean	18.03	26.92	33.46	35.24	41.02
		14	21	28	35	42
Small	1	30.57	34.12	36.26	36.93	37.04
	2	34.51	37.06	36.66	38.28	37.10
	3	32.15	36.32	36.08	36.02	36.89
	mean	32.41	35.83	36.33	37.08	37.01
Medium	1	35.63	32.98	38.39	36.77	38.02
	2	36.87	34.35	38.85	36.12	39.15
	3	36.28	34.91	37.49	34.82	37.70
	mean	36.26	34.08	38.24	35.90	38.29
Large	1	39.07	40.00	38.90	41.26	42.26
	2	43.28	41.05	42.76	42.70	43.71
	3	40.70	42.59	42.20	43.27	43.50
	mean	41.02	41.24	41.29	42.41	43.16

Table A5.22 Moisture content of 0-10 mm layer of unconfined soil clods at different wetting times (percentage dry basis). Initial moisture content = 38.81% (dry basis).

Clod size	Block	Wetting time (days)				
		0	1	3	5	7
Small	1	38.08	39.07	40.47	41.35	43.82
	2	37.72	40.12	43.55	42.63	42.23
	3	38.91	38.59	41.70	42.79	42.25
	mean	38.24	39.26	41.91	42.26	42.77
Medium	1	38.80	41.74	40.93	41.82	43.34
	2	38.85	41.56	41.47	43.27	42.12
	3	38.66	41.26	42.65	44.07	42.92
	mean	38.77	41.52	41.68	43.05	42.79
Large	1	38.91	40.27	41.57	42.30	43.15
	2	39.55	40.94	41.92	42.72	44.49
	3	38.73	40.38	41.43	42.87	43.49
	mean	39.06	40.53	41.64	42.63	43.71
		14	21	28	35	42
Small	1	44.21	44.66	42.51	44.78	44.48
	2	42.54	42.66	44.16	44.76	43.07
	3	44.61	43.30	44.30	44.52	42.36
	mean	43.79	43.54	43.66	44.69	43.30
Medium	1	42.10	42.56	43.61	45.52	47.46
	2	44.77	45.31	45.87	48.33	48.25
	3	45.74	45.49	46.93	46.99	46.45
	mean	44.20	44.45	45.47	46.95	47.39
Large	1	43.16	41.24	44.34	44.13	44.67
	2	44.14	42.11	43.05	43.97	44.79
	3	44.08	42.54	46.05	46.10	44.62
	mean	43.79	41.96	44.48	44.73	44.69

Table A5.23 Moisture content of 0-10 mm layer of confined clods at different wetting times (percentage dry basis).

a) Initial moisture content = 11.19%

Clod size	Block	Wetting time (days) 0	1	2	3	4	5	6	7
Small	1	9.84	36.88	38.81	39.70	38.95	38.97	38.88	39.26
	2	9.44	37.13	38.40	40.41	37.55	39.27	38.74	39.37
	3	10.98	37.40	37.65	40.01	40.39	39.42	37.96	38.93
	mean	10.09	37.14	38.29	40.04	38.96	39.22	38.53	39.19
Medium	1	11.23	36.75	40.18	41.12	39.41	37.46	39.82	40.89
	2	10.77	37.46	39.86	38.05	38.53	38.95	40.60	42.31
	3	9.42	36.39	38.05	37.80	38.24	38.58	39.53	41.37
	mean	10.47	36.87	39.36	38.99	38.73	38.33	39.98	41.52
Large	1	10.53	33.04	37.78	39.78	39.23	42.79	41.35	41.07
	2	9.43	32.05	36.67	37.95	39.00	41.87	40.19	40.45
	3	10.10	31.69	36.24	38.15	37.63	41.04	39.66	39.39
	mean	10.02	32.26	36.89	38.63	38.62	41.90	40.40	40.30

b) Initial moisture content = 21.31% (dry basis)

Clod size	Block	Wetting time (days) 0	1	2	3	4	5	6	7
Small	1	20.85	33.45	34.92	38.33	38.23	40.20	40.12	41.30
	2	19.12	34.41	34.80	38.10	39.00	39.17	40.29	40.30
	3	20.29	33.27	35.32	38.48	39.71	39.92	39.80	41.32
	mean	20.09	33.71	35.01	38.30	38.98	39.76	40.07	40.97
Medium	1	18.47	31.47	36.53	36.41	38.39	39.19	38.87	40.01
	2	19.15	32.16	35.93	37.20	38.62	39.24	38.44	40.00
	3	19.61	32.80	33.90	36.25	36.89	39.20	38.55	40.15
	mean	19.08	32.14	35.45	36.62	37.97	39.21	38.62	40.05
Large	1	17.39	25.86	31.33	33.39	34.75	34.72	36.26	41.07
	2	17.95	30.06	31.06	34.47	35.87	35.84	37.43	39.39
	3	19.33	30.59	31.29	37.11	38.63	38.59	40.31	39.66
	mean	18.22	28.84	31.23	34.99	36.42	36.38	38.00	40.04

c) Initial moisture content = 37.57% (dry basis)

Clod size	Block	Wetting time (days) 0	1	2	3	4	5	6	7
Small	1	37.05	38.55	38.39	39.12	38.86	38.78	39.61	38.63
	2	36.93	38.07	38.38	39.59	37.74	39.04	39.79	40.48
	3	37.89	37.92	38.03	39.17	39.11	38.67	39.82	39.64
	mean	37.28	38.18	38.27	39.29	38.57	38.83	39.74	39.58
Medium	1	38.21	38.48	38.41	39.14	38.48	38.81	40.22	38.97
	2	37.65	38.13	37.32	39.26	38.42	38.23	39.59	38.19
	3	37.86	38.40	37.73	38.04	38.86	37.89	39.32	38.76
	mean	37.90	38.34	37.82	38.81	38.59	38.31	39.71	38.64
Large	1	37.28	39.91	39.37	39.24	39.43	40.36	38.95	40.27
	2	37.70	40.36	39.81	39.68	39.87	40.81	39.39	40.73
	3	37.47	40.11	39.57	39.44	39.63	40.57	39.15	40.48
	mean	37.48	40.13	39.58	39.45	39.64	40.58	39.16	40.49

Table A5.24 Moisture distribution within unconfined clods wetted for different times (mean of three replicates). Initial moisture content was 12.74% (dry basis) and suction was at 10 cm.

a) Small clod

Wetting period (days)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	10.60	12.69	14.19	12.98	11.30	12.35
1	34.45	31.75	13.29	10.99	10.81	20.86
3	32.93	30.05	17.65	15.24	14.32	21.99
5	33.06	32.86	25.34	24.59	23.99	27.94
7	33.26	33.24	32.71	31.77	30.65	32.12
14	34.57	34.12	33.48	33.04	32.20	33.48
21	39.17	34.68	32.98	31.57	31.13	33.91
28	36.54	35.91	35.24	34.18	33.80	35.25
35	37.07	36.06	35.46	35.25	34.48	35.66
42	38.61	37.57	36.83	36.37	35.74	37.02

b) Medium clod

Wetting period (days)	Soil layer, mm					
	0-10	10-20	20-30	30-40	40-50	mean
0	11.03	14.17	14.58	12.43	10.99	12.82
1	30.73	13.76	12.32	11.35	12.97	16.58
3	30.60	17.03	14.99	14.57	13.95	18.69
5	32.88	23.16	22.66	19.43	15.81	23.55
7	35.96	34.13	33.92	30.23	29.41	33.15
14	40.25	38.25	32.86	26.38	25.35	33.37
21	38.87	35.58	33.91	31.66	30.63	34.51
28	39.58	36.21	34.53	32.27	31.22	35.15
35	36.74	36.49	34.30	32.85	32.11	34.54
42	37.13	35.44	33.28	31.51	30.74	32.94

c) Large clod

Wetting period (days)	Soil layer, mm						
	0-10	10-20	20-30	30-40	40-50	50-65	mean
0	9.40	13.12	14.58	15.11	14.35	11.80	13.06
1	28.60	17.03	16.59	15.95	15.47	13.87	17.92
3	35.67	19.47	16.75	15.65	14.85	13.47	19.15
5	38.80	33.17	23.46	22.00	21.38	20.40	26.54
7	38.24	32.99	32.81	32.74	32.15	27.32	32.71
14	37.28	36.31	36.04	35.68	35.21	34.89	35.90
21	38.45	37.17	36.53	36.07	35.82	34.61	36.44
28	38.96	37.65	37.01	36.54	36.30	35.07	36.92
35	39.26	37.94	37.29	36.83	36.57	35.34	37.54
42	40.34	38.99	38.32	37.84	37.58	36.31	38.90

Table A5.25 Moisture distribution within unconfined clods wetted for different times (mean three replicates). Initial moisture content was 21.76% (dry basis) and suction was at 10 cm.

a) small clod

Wetting period (days)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	19.05	22.53	23.86	22.03	21.37	21.77
1	28.22	26.84	23.75	22.84	21.70	24.67
3	27.35	27.08	26.59	26.20	25.00	26.46
5	32.98	28.77	28.02	28.20	26.43	28.88
7	31.01	30.80	30.40	30.21	29.20	30.32
14	32.69	32.12	31.58	30.75	29.97	31.42
21	36.54	34.64	34.15	32.29	31.15	33.75
28	37.42	35.32	33.85	33.89	33.53	34.82
35	37.20	36.95	36.46	36.24	35.03	36.37
42	37.28	36.78	36.75	35.74	34.91	36.29

b) Medium clod

Wetting period (days)	Soil layer,mm					
	0-10	10-20	20-30	30-40	40-50	mean
0	19.43	23.67	24.19	21.97	18.95	21.53
1	26.98	24.94	23.57	22.17	20.52	23.98
3	27.75	26.46	26.27	25.39	23.68	26.15
5	30.11	27.96	25.85	24.22	23.04	26.58
7	32.56	29.14	27.81	26.26	24.11	28.40
14	36.26	32.60	30.47	28.69	26.52	31.39
21	34.08	33.88	33.48	32.24	31.20	33.17
28	38.24	34.81	32.07	30.65	29.48	33.45
35	35.91	35.69	34.34	33.41	32.43	34.57
42	38.29	36.41	33.84	31.69	29.87	34.48

c) Large clod

Wetting period (days)	Soil layer,mm						
	0-10	10-20	20-30	30-40	40-50	50-65	mean
0	18.03	22.34	24.32	24.77	22.85	19.77	22.01
1	26.92	26.02	24.41	23.38	21.88	18.77	23.57
3	33.46	27.79	26.90	26.19	22.90	20.05	26.22
5	35.24	31.16	28.85	27.74	25.79	23.97	28.79
7	41.02	36.39	30.50	28.36	25.77	23.96	30.99
14	41.00	38.11	35.27	28.16	27.43	24.72	32.45
21	41.24	39.64	33.76	29.29	27.35	25.45	32.78
28	41.29	38.82	32.79	30.95	28.89	26.51	33.24
35	42.41	40.15	36.78	30.80	29.79	26.23	34.36
42	42.75	40.66	38.19	31.22	30.24	28.14	35.20

Table A5.26 Moisture distribution within unconfined clods wetted for different times (mean of three replicates). Initial moisture content was 38.81% (dry basis) and suction was at 10 cm.

a) small clod

Wetting period (days)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	38.04	38.43	38.72	38.47	37.98	38.33
1	39.39	39.12	39.53	38.72	38.04	38.96
3	42.53	41.28	40.82	40.76	40.09	41.25
5	43.09	41.41	41.13	40.92	40.12	41.33
7	43.17	42.36	41.94	41.49	41.34	42.06
14	43.96	43.61	42.87	42.53	41.35	42.86
21	43.78	43.29	42.77	42.39	41.60	42.77
28	43.85	43.40	43.15	42.91	42.30	43.13
35	44.88	44.49	43.97	43.78	43.69	44.16
42	43.64	42.96	42.58	42.43	41.83	42.69

b) Medium clod

Wetting period (days)	Soil layer, mm				
	0-5	5-10	10-15	15-20	20-25
0	38.35	39.19	39.48	39.03	38.62
1	42.65	40.39	39.31	39.06	38.49
3	41.97	41.39	41.24	40.90	40.15
5	43.69	42.41	41.31	41.27	40.69
7	44.03	41.55	40.08	40.21	39.88
14	45.11	43.29	42.63	41.21	40.93
21	45.20	43.70	41.62	41.14	40.28
28	45.84	45.10	45.00	44.32	43.33
35	47.98	45.92	44.94	43.56	43.12
42	48.43	46.34	45.35	43.96	43.52

	25-30	30-35	35-40	40-45	mean
0	38.51	38.93	39.22	38.48	38.83
1	38.38	38.28	38.18	38.12	39.20
3	39.81	39.46	39.02	38.98	40.32
5	40.33	40.06	39.65	39.31	40.96
7	39.21	39.05	38.90	38.55	40.16
14	40.82	40.38	40.30	40.95	41.40
21	40.15	40.05	40.03	39.69	41.31
28	42.69	42.02	41.88	41.32	44.32
35	42.90	42.26	41.47	40.38	43.62
42	43.30	42.64	41.86	40.75	44.02

c) Large clod

Wetting period (days)	Soil layer, mm						
	0-10	10-20	20-30	30-40	40-50	50-65	mean
0	39.06	39.20	39.30	39.32	39.57	39.24	39.28
1	40.53	40.30	40.21	39.49	39.19	39.13	39.81
3	41.64	40.85	39.65	39.36	39.15	39.06	40.74
5	42.63	41.33	39.59	39.48	38.97	38.89	40.15
7	43.71	42.11	41.10	40.80	40.73	39.73	41.36
14	43.79	42.33	40.51	39.93	39.84	39.58	40.99
21	41.96	41.16	40.78	40.42	40.35	39.78	39.95
28	44.48	42.99	41.14	40.56	40.46	40.20	41.63
35	44.73	43.24	41.37	40.79	40.69	40.43	41.87
42	44.69	43.20	41.34	40.75	40.65	40.40	41.83

Table A5.27 Moisture distribution within confined clods wetted for different times (mean of three replicates). Initial moisture content was 11.19% (dry basis) and suction was at 10 cm.

a) Small clod

Wetting Period (days)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	9.71	10.45	11.75	12.21	12.10	11.24
1	38.18	36.08	33.69	32.82	31.53	34.46
2	38.86	37.71	37.31	36.65	36.14	37.33
3	40.96	39.12	37.61	37.52	37.19	38.48
4	39.94	37.98	37.43	37.31	37.06	37.94
5	39.85	38.59	38.22	37.81	37.30	38.35
6	38.73	38.31	37.89	37.72	37.31	37.99
7	43.44	42.38	40.40	37.67	36.87	40.15

b) Medium clod

Wetting period (days)	Soil layer, mm					
	0-10	10-20	20-30	30-40	40-45	mean
0	10.47	12.10	12.44	13.15	-	11.88
1	36.87	34.37	31.29	27.64	-	31.81
2	39.36	36.96	35.34	34.98	-	36.66
3	38.99	36.67	36.60	34.73	-	36.08
4	38.73	37.22	36.27	35.12	-	36.84
5	38.33	37.64	36.15	35.20	-	36.83
6	39.98	38.23	37.01	36.55	-	37.94
7	41.52	37.23	36.29	35.37	-	37.60

c) Large clod

Wetting period (days)	Soil layer, mm						
	0-10	10-20	20-30	30-40	40-50	50-60	mean
0	10.02	11.83	12.31	12.52	13.35	-	12.01
1	32.26	30.31	29.29	22.17	18.33	16.16	24.75
2	36.90	34.67	34.36	26.76	24.11	18.25	29.18
3	38.63	36.08	35.60	35.08	36.07	22.42	31.31
4	38.62	36.59	36.63	35.57	36.58	34.34	36.39
5	41.90	39.48	37.75	36.22	37.99	34.72	38.01
6	40.40	37.98	36.44	36.27	37.53	35.12	37.28
7	40.30	38.07	37.05	36.67	37.60	35.77	37.58

Table A5.28 Moisture distribution within confined clods wetted for different times (mean of three replicates). Initial moisture content was 21.31% (dry basis)and suction was at 10 cm.

a) Small clod

Wetting period (days)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	19.85	20.48	20.84	22.18	-	20.83
1	33.98	33.44	32.75	31.30	30.28	32.35
2	35.15	34.87	33.74	33.07	30.60	33.49
3	39.16	37.45	35.80	34.86	33.99	36.25
4	39.07	38.89	38.26	37.35	35.87	37.89
5	40.18	39.34	38.71	37.95	37.54	38.74
6	40.77	39.36	38.76	38.60	37.74	39.04
7	41.29	40.66	40.35	39.78	38.85	40.19

b) Medium clod

Wetting period (days)	Soil layer, mm					
	0-10	10-20	20-30	30-40	40-45	mean
0	19.61	22.40	23.50	24.28	-	22.45
1	32.14	30.88	30.02	28.49	-	30.38
2	35.45	34.38	33.19	30.41	-	33.36
3	36.62	36.42	36.46	34.53	-	36.00
4	37.97	38.17	38.19	37.12	-	37.80
5	39.21	38.32	38.36	37.83	-	38.47
6	38.62	38.58	38.48	38.45	-	38.49
7	40.06	39.44	39.11	38.79	-	39.24

c) Large clod

Wetting period (days)	Soil layer, mm						
	0-10	10-20	20-30	30-40	40-50	50-60	mean
0	18.22	20.57	21.15	21.50	21.63	20.85	20.65
1	28.84	24.71	23.38	22.78	22.28	21.40	23.90
2	30.99	26.74	24.46	23.68	23.11	22.11	25.18
3	34.99	30.26	26.70	24.01	23.18	23.02	27.03
4	36.42	36.48	32.46	26.28	25.44	25.69	30.46
5	36.38	35.48	35.40	30.63	28.55	27.36	32.30
6	38.00	36.55	36.38	34.80	35.19	32.45	35.56
7	40.04	39.13	38.25	36.84	36.77	36.26	37.88

Table A5.29 Moisture distribution within confined clods wetted for different times (mean of three replicates). Initial moisture content was 37.57% (dry basis) and suction was at 10 cm.

a) Small clod

Wetting period (days)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	37.16	37.28	37.08	37.23	36.04	36.96
1	38.41	37.95	38.03	37.15	37.10	37.73
2	38.50	38.03	38.07	37.67	37.44	37.94
3	39.59	38.91	38.88	38.10	37.91	38.70
4	38.47	38.66	38.21	38.36	37.43	38.23
5	39.08	38.58	38.06	37.98	37.79	38.30
6	39.92	39.55	38.96	38.82	38.64	39.18
7	39.80	39.36	38.97	38.50	38.20	38.96

b) Medium clod

Wetting period (days)	Soil layer, mm					
	0-10	10-20	20-30	30-40	40-45	mean
0	37.87	37.84	38.10	37.87	37.09	37.84
1	38.34	37.92	37.20	37.12	37.31	37.60
2	38.11	37.65	37.28	36.98	37.00	37.47
3	38.81	37.84	37.09	37.15	37.04	37.65
4	38.59	37.82	37.53	37.34	36.64	37.69
5	38.31	37.86	37.77	37.29	36.66	37.68
6	39.71	38.86	38.20	37.85	37.26	38.50
7	38.64	38.10	37.61	37.43	37.01	37.84

c) Large clod

Wetting period (days)	Soil layer, mm							
	0-10	10-20	20-30	30-40	40-50	50-60	60-65	mean
0	37.48	37.80	38.06	38.07	38.25	37.94	37.90	37.93
1	40.13	39.33	38.99	38.55	39.25	38.68	37.68	38.94
2	39.58	38.76	38.58	38.54	38.52	38.26	37.25	38.50
3	39.45	38.20	38.12	37.46	37.53	36.82	36.59	37.74
4	39.64	39.22	38.82	38.35	38.74	38.12	37.29	38.60
5	40.58	39.93	39.62	39.39	39.41	38.92	37.64	39.35
6	39.16	38.79	38.53	38.21	39.27	38.10	38.03	38.59
7	40.49	39.19	38.73	39.71	38.27	38.45	37.83	38.95

Table A5.30 Depth of cone penetration for different wetting times. Units are in mm.

a) Initial moisture content = 21.31% (dry basis).

Clod size	Block	Wetting time (days)							
		0	1	2	3	4	5	6	7
Small	1	0.6	2.6	2.4	2.8	2.9	2.9	3.0	3.0
	2	0.5	2.3	2.8	2.5	2.8	2.7	2.8	3.0
	3	0.6	2.6	2.6	2.8	2.5	2.8	2.7	2.7
	mean	0.6	2.5	2.6	2.7	2.7	2.8	2.8	2.8
Medium	1	0.7	2.5	2.5	2.5	2.8	2.6	2.9	2.6
	2	0.8	2.8	2.9	2.6	2.4	2.8	2.6	2.5
	3	0.8	2.5	2.4	2.8	2.9	2.8	2.6	2.8
	mean	0.8	2.6	2.6	2.6	2.7	2.7	2.7	2.6
Large	1	0.7	2.6	2.4	2.2	2.6	2.5	2.7	2.7
	2	0.7	2.0	2.2	2.4	2.3	2.4	2.4	2.5
	3	0.6	1.8	2.2	2.2	2.3	2.6	2.8	2.6
	mean	0.7	2.1	2.3	2.3	2.4	2.5	2.6	2.6

b Initial moisture content = 37.57% (dry basis).

Clod size	Block	Wetting time (days)							
		0	1	2	3	4	5	6	7
Small	1	2.7	2.9	2.9	2.9	2.8	2.8	3.0	2.9
	2	2.7	2.5	2.7	2.9	2.6	3.1	2.9	3.2
	3	2.6	2.7	2.7	2.6	2.9	3.0	3.0	3.0
	mean	2.7	2.7	2.8	2.8	2.7	3.0	3.0	3.0
Medium	1	2.8	3.0	2.7	3.0	2.9	3.0	3.2	3.0
	2	2.6	2.9	2.7	3.1	2.6	3.1	2.7	2.7
	3	2.6	2.5	3.0	2.6	2.9	2.6	2.8	2.7
	mean	2.7	2.8	2.8	2.9	2.8	2.9	2.9	2.8
Large	1	2.6	2.8	2.8	2.9	2.9	2.9	2.7	2.6
	2	2.7	2.5	2.8	2.6	2.5	2.6	2.7	3.0
	3	2.8	2.9	2.6	2.9	2.6	3.0	2.9	2.9
	mean	2.7	2.7	2.7	2.8	2.7	2.8	2.8	2.8

Table A5.31 Volume of clods after different drying times (cm^3).

Clod size	Block	Drying time (hours)					
		0	4	8	12	16	20
Small	1	17.51	15.82	14.81	13.71	12.12	12.69
	2	18.92	17.09	15.58	13.57	13.37	12.62
	3	18.57	16.78	14.46	13.99	13.74	12.81
	mean	18.33	16.56	15.02	13.76	13.08	12.71
Medium	1	100.64	96.53	94.93	88.42	79.49	85.50
	2	108.72	104.28	99.87	87.51	87.69	85.03
	3	106.75	102.39	92.69	90.22	90.12	86.31
	mean	105.35	101.05	96.28	88.74	85.79	85.64
Large	1	278.35	273.96	263.68	265.07	243.36	253.75
	2	300.76	295.95	283.13	262.37	268.46	252.35
	3	295.20	290.58	262.60	270.49	275.89	256.15
	mean	291.38	286.77	272.95	266.04	262.64	254.15
		24	48	72	96	120	
Small	1	13.20	12.81	12.37	12.46	12.35	
	2	12.65	12.35	12.11	12.58	12.24	
	3	12.57	12.87	12.96	12.97	11.82	
	mean	12.81	12.68	12.48	12.67	12.14	
Medium	1	87.47	74.92	72.60	73.13	71.02	
	2	83.83	72.22	71.08	73.84	70.39	
	3	83.30	75.27	76.07	76.13	67.97	
	mean	84.89	74.16	73.25	74.37	69.81	
Large	1	250.95	233.43	220.87	209.45	209.78	
	2	240.49	225.05	216.22	211.47	207.91	
	3	238.98	234.52	231.40	218.02	200.77	
	mean	243.54	231.06	222.83	212.98	206.21	

Least significant difference = 8.92

Table A5.32 Dry bulk density of clods dried for different times (Mg/m^3).

Clod size	Block	Drying time (hours)										
		0	4	8	12	16	20	24	48	72	96	120
Small	1	1.28	1.41	1.61	1.64	2.03	1.82	1.78	1.87	1.88	1.99	1.94
	2	1.27	1.40	1.46	1.62	1.85	1.85	1.93	1.97	1.96	1.88	1.85
	3	1.30	1.44	1.60	1.62	1.67	1.86	1.97	1.79	1.90	1.83	1.95
	mean	1.29	1.42	1.56	1.63	1.85	1.84	1.89	1.88	1.91	1.90	1.90
Medium	1	1.28	1.35	1.47	1.52	1.68	1.53	1.47	1.78	1.81	1.96	1.91
	2	1.27	1.34	1.33	1.50	1.50	1.56	1.59	1.88	1.89	1.85	1.86
	3	1.30	1.38	1.46	1.50	1.41	1.57	1.63	1.70	1.83	1.80	2.00
	mean	1.29	1.36	1.42	1.51	1.53	1.55	1.56	1.79	1.84	1.87	1.91
Large	1	1.28	1.33	1.43	1.42	1.57	1.45	1.44	1.62	1.68	1.83	1.84
	2	1.27	1.32	1.30	1.40	1.43	1.48	1.56	1.71	1.75	1.77	1.80
	3	1.30	1.36	1.43	1.40	1.29	1.49	1.59	1.55	1.70	1.76	1.92
	mean	1.29	1.34	1.39	1.41	1.43	1.47	1.53	1.63	1.71	1.79	1.84

Least significant difference = 0.19

Table A5.33 Moisture distribution within clods dried at 25^{0}C (mean of three replicates). Moisture content units are in percentage dry basis.

a) Small cube

Drying time (hours)	Soil layer, mm					
	0-5	5-10	10-15	15-20	20-25	mean
0	39.04	39.43	39.72	39.47	38.98	39.33
4	26.16	29.17	30.27	30.71	27.83	28.83
8	20.43	23.37	25.31	24.49	23.59	23.44
12	18.44	20.94	21.76	20.38	19.93	20.30
16	11.41	13.95	15.90	13.91	11.87	13.41
20	9.70	11.86	13.22	11.99	10.54	11.46
24	7.11	9.05	10.52	9.51	8.54	8.95
48	5.37	5.96	6.57	6.12	5.47	5.90
72	4.76	5.13	5.43	4.90	4.20	4.88
96	3.42	5.06	5.80	4.65	3.52	4.46
120	3.47	3.97	5.66	4.59	4.08	4.35

b) Medium cube

Drying time (hours)	Soil layer, mm									
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	mean
0	38.35	39.19	39.48	39.03	38.62	38.51	38.93	39.22	38.48	38.87
4	29.38	32.62	34.21	34.94	35.56	35.24	34.31	33.39	31.28	33.44
8	26.60	29.12	30.65	31.63	31.99	31.37	30.19	28.08	24.31	29.33
12	23.90	24.93	26.57	27.42	28.18	27.78	26.40	25.34	23.24	25.97
16	18.83	22.06	24.66	26.12	26.67	26.37	26.36	24.65	22.51	24.25
20	17.15	19.72	21.35	22.60	22.34	21.44	19.64	17.34	15.46	19.79
24	12.67	14.73	16.29	16.79	17.11	16.79	15.84	14.59	13.86	15.90
48	9.22	11.43	13.15	13.92	13.91	13.99	12.42	11.68	10.23	12.22
72	6.02	8.82	9.29	10.02	10.28	9.27	9.74	8.35	7.93	8.86
96	6.99	7.86	8.99	9.08	9.71	9.26	8.84	8.39	7.53	8.52
120	6.08	6.75	7.41	7.58	7.99	8.08	7.44	7.21	6.67	7.25

c) Large cube

Drying time (hours)	Soil layer, mm						
	0-10	10-20	20-30	30-40	40-50	50-65	Mean
0	39.06	39.20	39.30	39.32	39.57	39.24	39.28
4	33.52	36.52	36.44	36.77	36.04	34.75	35.67
8	29.89	33.86	34.83	35.75	34.82	32.98	33.68
12	26.60	31.06	33.54	33.26	33.38	32.43	31.71
16	25.87	31.61	33.16	33.64	32.60	26.91	30.63
20	23.46	29.25	31.67	32.19	30.21	25.75	28.76
24	21.74	26.38	28.68	29.47	27.94	24.11	26.39
48	17.52	21.79	23.73	24.13	22.16	19.18	21.42
72	13.27	18.05	21.28	20.50	17.69	14.24	17.51
96	9.40	13.12	14.58	15.11	14.35	11.80	13.06
120	10.96	13.55	14.38	14.08	12.56	10.47	12.67

Table A5.34 Moisture content of 0-10 mm layer of soil clods at different drying time (percentage dry basis).

Clod size	Block	Drying time (hours) 0	4	8	12	16	20
Small	1	39.19	25.61	21.00	19.27	10.08	9.30
	2	39.10	28.87	22.45	19.72	12.65	11.33
	3	39.43	29.22	21.36	20.30	12.04	10.63
	mean	39.24	27.90	21.60	19.76	11.59	10.42
Medium	1	38.80	30.23	26.50	23.34	21.51	17.88
	2	38.66	31.93	28.92	24.55	20.10	18.97
	3	38.85	30.85	28.16	25.36	19.73	18.48
	mean	38.77	31.00	27.86	24.42	20.45	18.44
Large	1	38.91	33.39	29.77	26.49	25.77	23.37
	2	39.55	33.94	30.26	26.93	26.19	23.75
	3	38.73	33.24	29.63	26.37	25.65	23.26
	mean	39.06	33.52	29.89	26.60	25.87	23.46

Clod size	Block	24	48	72	96	120
Small	1	7.64	5.59	5.89	4.77	4.18
	2	7.32	5.20	5.45	4.84	3.87
	3	9.11	6.02	5.48	5.14	4.89
	mean	8.02	5.60	5.61	4.92	4.31
Medium	1	13.54	10.05	7.35	7.21	6.33
	2	13.72	10.68	7.04	7.61	6.48
	3	13.85	10.25	7.87	7.47	6.44
	mean	13.70	10.33	7.42	7.43	6.42
Large	1	21.65	17.45	13.22	10.92	9.36
	2	22.01	17.74	13.44	11.10	9.51
	3	21.55	17.37	13.16	10.87	9.32
	mean	21.74	17.52	13.27	10.96	9.40

Least significant difference = 1.09

Table A5.35 Bridge Outputs (Dynamometer Loaded Vertically)

Load (N)	Channel output(mV)		
	Fx	Fz	My
49.05	0.00	4.88	6.00
107.91	0.23	9.90	12.00
156.96	0.78	14.88	18.00
206.01	0.13	19.68	24.00
255.06	0.13	24.48	30.00
304.11	0.15	29.43	36.00
353.16	0.15	34.23	42.00
402.21	0.15	39.18	48.00
451.26	0.15	44.20	54.00
500.31	0.15	48.83	60.00

Table A5.36 Bridge Outputs (Dynamometer Loaded Horizontally)

a) Fx Bridge Output (mV)

Load (N)	Loading Positions From Centroid (mm)		
	100	350	680
127.53	11.15	11.98	11.73
255.06	23.05	23.28	23.33
372.78	33.93	34.35	33.88
500.31	44.33	43.95	46.55
627.84	56.15	57.85	57.58
745.56	67.40	67.83	67.75
873.09	79.45	79.70	79.38
1001	90.28	90.35	90.40

b) Fz and My Bridge Outputs (mV)

Moment (Nm)	Channel	
	Fz	My
12.75	0.20	3.00
25.51	0.43	7.08
37.28	0.70	10.63
50.03	0.95	14.03
62.78	1.15	17.45
74.56	1.45	22.00
87.31	1.75	26.70
100.00	2.13	30.70
132.5	0.70	38.65
175.00	0.95	52.70
219.74	1.15	65.88
260.74	1.45	79.08
305.58	1.75	100.70
350.00	2.13	109.30
426.93	1.15	124.55
506.98	1.45	155.35
593.70	1.75	187.80
680.00	2.13	202.50

Table A5.37 Average side disturbance from tine side at 42% moisture content (dry basis). Units are in mm.

Depth (mm)	Rake angle (degrees)	Block	Width of tine(mm)	
			25.4	50.8
50.8	45	1	32.30	34.60
		2	32.30	34.60
		3	32.30	34.60
		mean	32.60	34.60
	90	1	32.30	39.60
		2	37.30	39.60
		3	32.30	44.60
		mean	33.97	41.27
	135	1	37.30	44.60
		2	42.30	44.60
		3	42.30	49.60
		mean	40.63	46.30
101.6	45	1	37.30	49.60
		2	37.30	44.60
		3	42.30	44.60
		mean	38.90	46.30
	90	1	42.30	49.60
		2	42.30	49.60
		3	42.30	49.60
		mean	42.30	49.60
	135	1	52.30	59.60
		2	52.30	59.60
		3	52.30	64.60
		mean	52.30	61.27
152.4	45	1	39.30	51.60
		2	39.30	49.60
		3	42.30	49.60
		mean	40.30	50.30
	90	1	47.30	54.60
		2	47.30	54.60
		3	47.30	54.60
		mean	47.30	54.60
	135	1	62.40	72.90
		2	63.20	79.30
		3	59.10	85.90
		mean	61.60	79.40

Table A5.38 Average side disturbance (mm) from tine side at 56% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Block	Width of tine (mm) 25.4	50.8
50.8	45	1	37.30	44.60
		2	37.30	44.60
		3	32.30	44.60
		mean	35.60	44.60
	90	1	42.30	49.60
		2	42.30	49.60
		3	42.30	44.60
		mean	42.30	47.90
	135	1	52.30	59.60
		2	52.30	59.60
		3	52.30	59.60
		mean	52.30	59.60
101.6	45	1	47.30	59.60
		2	47.30	59.60
		3	52.30	64.60
		mean	48.90	61.30
	90	1	52.30	64.60
		2	52.30	64.60
		3	52.30	64.60
		mean	52.30	64.60
	135	1	67.30	84.60
		2	67.30	84.60
		3	72.30	84.60
		mean	68.90	84.60
152.4	45	1	52.30	64.60
		2	47.30	64.60
		3	52.30	64.60
		mean	50.60	64.60
	90	1	54.30	69.60
		2	54.30	69.60
		3	57.30	69.60
		mean	55.30	69.60
	135	1	80.40	103.60
		2	81.30	112.60
		3	81.70	112.60
		mean	81.10	109.60

Table A5.39 Average side disturbance (mm) from tine side for three depths at 70% moisture content.

Depth (mm)	Rake angle (degrees)	Block	Width of tine(mm) 25.4	50.8	101.6	152.4
50.8	45	1	37.30	54.60	24.20	23.80
		2	37.30	49.60	24.20	23.80
		3	37.30	49.60	29.20	23.80
		mean	37.30	52.30	25.90	23.80
	90	1	47.30	54.60	29.20	33.80
		2	52.30	59.60	34.20	28.80
		3	52.30	49.60	29.20	33.80
		mean	50.60	54.60	30.90	32.10
	135	1	57.30	69.60	64.20	73.80
		2	57.30	64.60	69.20	68.80
		3	57.30	64.60	69.20	73.80
		mean	57.30	66.30	67.50	72.10
101.6	45	1	52.30	64.60	39.20	33.80
		2	52.30	74.60	34.20	33.80
		3	47.30	64.60	34.20	38.80
		mean	50.60	67.90	35.90	35.50
	90	1	67.30	79.60	49.20	38.80
		2	62.30	74.60	49.20	43.80
		3	62.30	79.60	54.20	38.80
		mean	63.90	77.90	50.90	40.50
	135	1	77.30	93.60	84.20	88.80
		2	72.30	93.60	84.20	88.80
		3	77.30	93.60	89.20	93.80
		mean	75.60	93.60	85.90	90.50
152.4	45	1	62.30	67.30	-	-
		2	62.30	87.30	-	-
		3	57.30	77.30	-	-
		mean	60.60	77.30	-	-
	90	1	69.60	94.60	-	-
		2	69.60	94.60	-	-
		3	69.60	84.60	-	-
		mean	69.60	91.30	-	-
	135	1	92.30	114.60	-	-
		2	87.30	124.60	-	-
		3	87.30	124.60	-	-
		mean	88.90	121.30	-	-

Table A5.40 Average height of heave at different lateral distance from the side of tine for three depths and rake angles (42% moisture content)

a) 25.4 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	20	6	6	4
	40	0	0	0
90	20	2	5	6
	40	2	3	5
	60	0	0	0
135	20	11	13	15
	40	0	10	8
	60	0	0	3
	80	0	0	0

b) 50.8 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	20	8	14	12
	40	0	4	9
	60	0	0	0
90	20	4	4	0
	40	0	2	3
	60	0	0	0
135	20	12	12	14
	40	0	8	12
	60	0	2	5
	80	0	0	0

Table A5.41 Average height of heave at different lateral distance from the side of tine for three depths and rake angles (56 % moisture content)

a) 25.4 mm tine

Rake angle (degrees)	Lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	20	4	8	10
	40	0	7	7
	60	0	0	0
90	20	14	21	21
	40	10	10	10
	60	0	0	0
135	20	17	20	20
	40	9	16	18
	60	0	2	8
	80	0	0	0

b) 50.8 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	20	7	15	12
	40	1	9	10
	60	0	2	4
	80	0	0	0
90	20	13	22	22
	40	12	17	24
	60	0	2	8
	80	0	0	0
135	20	28	39	21
	40	18	29	26
	60	0	15	22
	80	0	2	14
	100	0	0	5
	120	0	0	0

Table A5.42 Average height of heave at different lateral distance from the side of tine for three depths and rake angles (70 % moisture content).

a) 25.4 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	20	10	22	26
	40	0	7	19
	60	0	0	0
90	20	18	21	23
	40	6	12	14
	60	0	4	6
	80	0	0	0
135	20	12	10	14
	40	6	5	6
	60	0	2	4
	80	0	0	2
	100	0	0	0

b) 50.8 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	20	10	34	25
	40	3	13	19
	60	0	1	9
	80	0	0	2
	100	0	0	0
90	20	17	26	37
	40	7	17	27
	60	0	5	10
	80	0	0	2
	100	0	0	0
135	20	29	24	20
	40	22	19	16
	60	5	8	10
	80	0	3	5
	100	0	0	3
	120	0	0	0

c) 101.6 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	10	12	25	-
	20	5	18	-
	30	0	0	-
90	10	15	22	-
	20	9	19	-
	30	0	11	-
	40	0	4	-
	50	0	0	-
135	20	34	37	-
	40	22	24	-
	60	4	13	-
	80	0	4	-
	100	0	0	-

d) 152.4 mm tine

Rake angle (degrees)	lateral distance (mm)	Depth (mm)		
		50.8	101.6	152.4
45	10	14	19	-
	20	5	10	-
	30	0	4	-
	40	0	0	-
90	10	13	20	-
	20	11	13	-
	30	0	6	-
	40	0	0	-
135	20	25	27	-
	40	15	25	-
	60	7	14	-
	80	0	4	-
	100	0	0	-

Table A5.43 Mean draught force (N) over three blocks for three depths at 42% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Block	Width of tine (mm)	
			25.4	50.8
50.8	45	1	131.14	198.58
		2	140.96	216.40
		3	154.64	228.51
		mean	142.25	214.50
	90	1	224.91	277.32
		2	207.45	299.86
		3	211.14	281.84
		mean	214.50	286.34
	135	1	340.03	520.25
		2	302.22	489.06
		3	306.06	527.11
		mean	316.10	512.14
101.6	45	1	325.72	444.84
		2	301.59	484.77
		3	356.07	511.90
		mean	327.79	480.50
	90	1	383.13	609.01
		2	355.25	684.24
		3	389.76	711.31
		mean	376.05	679.98
	135	1	646.45	1162.38
		2	613.24	1092.66
		3	653.74	1177.70
		mean	637.81	1144.25
152.4	45	1	460.00	716.45
		2	540.00	810.00
		3	501.08	790.00
		mean	500.36	772.15
	90	1	535.00	839.00
		2	580.00	890.14
		3	550.27	910.74
		mean	555.09	879.96
	135	1	1159.33	1889.12
		2	1400.00	1950.00
		3	1350.00	1900.00
		mean	1303.11	1913.04

Table A5.44 Mean draught force (N) over three blocks for three depths at 56% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Block	Width of tine (mm)	
			25.4	50.8
50.8	45	1	76.01	112.13
		2	82.18	119.10
		3	77.25	123.81
		mean	78.48	118.35
	90	1	98.68	196.19
		2	91.02	173.37
		3	92.64	181.11
		mean	94.12	183.56
	135	1	160.78	286.11
		2	172.83	272.47
		3	189.59	289.09
		mean	174.40	282.56
101.6	45	1	168.95	241.70
		2	182.53	270.93
		3	191.07	262.93
		mean	180.85	258.52
	90	1	216.17	370.02
		2	201.91	361.29
		3	219.57	325.89
		mean	212.55	352.40
	135	1	350.54	554.20
		2	334.91	581.51
		3	370.21	559.66
		mean	351.89	565.12
152.4	45	1	250.31	425.90
		2	271.76	380.00
		3	314.24	419.00
		mean	278.77	408.30
	90	1	290.00	384.00
		2	310.00	425.52
		3	320.61	455.00
		mean	306.87	454.84
	135	1	750.55	1230.46
		2	790.00	1150.00
		3	720.10	1057.12
		mean	753.70	1145.82

Table A5.45 Mean draught force (N) over three blocks for three depths at 70% moisture content (dry basis)

Depth (mm)	Rake angle (degrees)	Block	Width of tine(mm) 25.4	50.8	101.6	152.4
50.8	45	1	32.70	48.35	66.26	85.89
		2	26.20	40.40	60.52	89.33
		3	29.40	44.39	60.24	82.45
		mean	29.43	44.38	62.34	85.89
	90	1	36.57	58.71	124.98	201.02
		2	40.20	65.61	128.44	161.06
		3	43.89	69.07	125.78	207.07
		mean	40.22	64.46	126.41	189.71
	135	1	59.46	114.27	222.36	313.92
		2	65.37	103.76	218.58	268.14
		3	71.36	99.84	226.32	294.30
		mean	65.40	105.96	222.42	292.12
101.6	45	1	67.82	98.26	149.12	193.03
		2	71.58	106.10	134.91	200.60
		3	64.06	100.04	143.13	182.15
		mean	67.82	101.47	142.39	191.93
	90	1	81.60	135.39	182.30	406.08
		2	88.65	142.51	186.02	399.53
		3	75.00	138.95	197.18	379.87
		mean	81.75	138.95	188.50	395.16
	135	1	156.18	231.75	392.40	575.18
		2	174.22	268.34	413.05	557.40
		3	163.58	256.14	405.48	600.82
		mean	164.66	252.07	403.64	577.80
152.4	45	1	122.95	145.94	-	-
		2	127.99	151.18	-	-
		3	103.78	155.70	-	-
		mean	118.24	150.94	-	-
	90	1	124.28	217.43	-	-
		2	130.57	223.65	-	-
		3	116.06	221.56	-	-
		mean	123.64	220.88	-	-
	135	1	328.52	398.71	-	-
		2	271.04	465.37	-	-
		3	295.68	423.51	-	-
		mean	298.42	429.20	-	-

Table A5.46 Mean vertical force (N) over three blocks for three depths at 42% moisture content (dry basis)

Depth (mm)	Rake angle (degrees)	Block	Width of tine (mm) 25.4	50.8
50.8	45	1	-49.95	-153.91
		2	-54.01	-144.67
		3	-50.77	-155.93
		mean	-51.58	-151.55
	90	1	46.10	133.07
		2	44.31	128.25
		3	44.69	128.77
		mean	45.03	130.03
	135	1	192.17	385.94
		2	206.56	420.59
		3	226.59	444.11
		mean	208.44	416.88
101.6	45	1	-82.46	-196.38
		2	-89.09	-212.33
		3	-93.26	-199.57
		mean	-88.27	-202.76
	90	1	54.75	155.64
		2	52.68	151.36
		3	55.23	133.97
		mean	54.22	146.99
	135	1	397.23	794.46
		2	379.50	759.01
		3	419.52	839.03
		mean	398.75	797.50
152.4	45	1	-100.72	-310.00
		2	-116.66	-328.00
		3	-104.99	-340.78
		mean	-107.46	-326.26
	90	1	55.99	138.90
		2	66.07	173.60
		3	72.16	162.40
		mean	63.25	158.30
	135	1	550.00	1236.00
		2	600.00	1150.60
		3	668.30	1250.00
		mean	606.10	1212.20

- indicates downward direction

Table A5.47 Mean vertical force (N) over three blocks for three depths at 56% moisture content (dry basis)

Depth (mm)	Rake angle (degrees)	Block	Width of tine (mm)	
			25.4	50.8
50.8	45	1	-26.91	-70.02
		2	-29.09	-63.78
		3	-27.35	-71.39
		mean	-27.78	-68.40
	90	1	31.78	49.95
		2	28.46	54.24
		3	29.16	55.30
		mean	29.80	53.16
	135	1	110.55	218.49
		2	115.53	238.10
		3	118.91	251.41
		mean	115.00	236.00
101.6	45	1	-41.80	-107.90
		2	-46.40	-121.43
		3	-49.59	-129.92
		mean	-45.93	-119.75
	90	1	33.48	56.73
		2	29.22	64.45
		3	34.48	75.28
		mean	32.39	65.46
	135	1	229.12	475.40
		2	218.90	450.45
		3	241.97	469.15
		mean	229.99	465.00
152.4	45	1	-42.79	-200.00
		2	-51.00	-195.00
		3	-50.01	-160.83
		mean	-47.93	-183.61
	90	1	38.81	92.14
		2	30.33	82.93
		3	27.99	87.31
		mean	36.27	87.46
	135	1	338.45	715.00
		2	352.00	685.00
		3	348.00	676.84
		mean	346.15	692.28

- indicates downward direction

Table A5.48 Mean vertical force (N) over three blocks for three depths at 70% moisture content (dry basis).

Depth (mm)	Rake angle (degrees)	Block	Width of tine(mm) 25.4	50.8	101.6	152.4
50.8	45	1	-14.29	-30.79	-60.40	-68.57
		2	-20.97	-34.21	-51.26	-64.00
		3	-16.62	-32.18	-54.93	-66.62
		mean	-15.53	-32.40	-55.54	-66.40
	90	1	9.97	17.37	56.90	69.80
		2	10.50	12.77	52.84	65.15
		3	8.95	14.70	44.49	67.81
		mean	9.81	14.95	50.32	67.59
	135	1	40.45	90.12	178.68	284.28
		2	53.05	89.19	181.43	259.20
		3	35.89	90.69	179.90	266.51
		mean	43.13	90.00	180.00	270.00
101.6	45	1	-31.31	-56.00	-91.72	-118.38
		2	-28.83	-54.10	-102.72	-132.12
		3	-31.86	-51.34	-107.33	-155.40
		mean	-30.66	-53.82	-100.58	-135.30
	90	1	18.07	34.63	51.99	103.37
		2	19.67	33.45	65.01	106.53
		3	15.57	31.75	73.14	98.20
		mean	17.77	33.28	63.38	102.70
	135	1	83.47	151.43	328.95	494.50
		2	89.43	181.73	346.26	524.47
		3	85.85	184.34	359.79	533.54
		mean	86.25	172.50	345.00	517.50
152.4	45	1	-58.40	-111.12	-	-
		2	-60.36	-113.63	-	-
		3	-67.43	-141.02	-	-
		mean	-62.08	-121.93	-	-
	90	1	19.13	55.58	-	-
		2	19.90	50.38	-	-
		3	16.59	62.53	-	-
		mean	18.54	56.16	-	-
	135	1	136.18	270.78	-	-
		2	129.55	216.63	-	-
		3	140.65	288.83	-	-
		mean	135.44	258.75	-	-

- indicates downward direction.

Table A5.49 Experimental results of multitines at three spacings and two leading tine positions for 56% moisture content (dry basis).

Treatment	Block	Draught(N)	Vertical force(N)
3 TA	1	389.60	56.99
	2	333.20	69.44
	3	326.66	67.57
	Mean	349.82	64.67
3 TB	1	648.30	78.21
	2	582.78	75.51
	3	664.65	62.01
	Mean	631.91	71.91
3 TC	1	388.60	73.19
	2	355.90	66.53
	3	362.44	90.52
	Mean	368.98	76.75
3 TD	1	659.25	68.99
	2	601.65	75.03
	3	665.90	84.89
	Mean	642.27	76.30
3 TE	1	395.14	85.63
	2	388.60	81.87
	3	404.95	72.48
	Mean	396.23	79.99
3 TF	1	650.20	86.93
	2	633.85	84.17
	3	699.25	70.59
	Mean	661.10	80.50

Table A5.50 Experimental results of multitines at three spacings and two leading tine positions for 70% moisture content (dry basis).

Treatment	Block	Draught(N)	Vertical force(N)
3 TA	1	115.44	52.80
	2	154.68	43.28
	3	141.60	40.54
	Mean	137.24	45.54
3 TB	1	232.40	70.40
	2	197.80	59.10
	3	248.75	72.66
	Mean	226.32	67.39
3 TC	1	147.76	56.88
	2	141.22	45.54
	3	151.03	47.80
	Mean	146.67	50.07
3 TD	1	223.50	67.80
	2	243.58	90.40
	3	223.04	70.60
	Mean	230.04	76.27
3 TE	1	130.84	61.70
	2	163.92	55.40
	3	167.00	56.70
	Mean	153.92	57.93
3 TF	1	187.80	83.00
	2	240.88	71.70
	3	237.61	73.96
	Mean	235.43	76.20

Table A5.51 Aggregate breakdown (%)*
a) Stirring time = 5 seconds

Sieve size (mm)	Water-soil ratio			
	0.8	1.0	1.2	1.4
> 2.0	49.54 (1.61)	22.68 (1.08)	23.59 (1.92)	25.33 (1.33)
1.0-2.0	5.34 (0.99)	11.30 (0.59)	10.64 (0.52)	10.98 (0.32)
0.5-1.0	4.86 (0.80)	12.68 (1.59)	10.70 (1.58)	12.46 (0.87)
0.25-0.50	5.79 (0.04)	10.06 (1.25)	11.39 (1.69)	15.17 (1.27)
0.125-0.25	2.92 (0.22)	7.29 (0.90)	9.68 (1.72)	5.26 (0.25)
< 0.125	31.55 (3.31)	35.99 (2.49)	41.15 (2.48)	30.80 (0.33)

b) Stirring time = 10 seconds

Sieve size (mm)	Water-soil ratio			
	0.8	1.0	1.2	1.4
> 2.0	36.84 (1.23)	23.77 (2.11)	23.74 (0.63)	20.01 (2.46)
1.0-2.0	7.30 (1.05)	11.11 (1.61)	9.12 (1.19)	11.41 (0.48
0.5-1.0	6.76 (0.93)	8.09 (0.49)	8.66 (0.46)	11.43 (1.06)
0.25-0.50	5.33 (1.30)	13.94 (0.15)	10.75 (0.99)	11.38 (1.74)
0.125-0.25	2.08 (0.53)	5.58 (0.26)	3.04 (0.96)	5.02 (0.86)
< 0.125	41.69 (1.04)	38.02 (1.45)	45.30 (1.92)	40.75 (3.05)

c) Stirring time = 20 seconds

Sieve size (mm)	Water-soil ratio			
	0.8	1.0	1.2	1.4
> 2.0	27.95 (1.06)	19.17 (1.66)	20.14 (0.93)	16.43 (0.93)
1.0-2.0	10.47 (0.36)	7.79 (0.26)	9.70 (0.56)	9.79 (1.21)
0.5-1.0	9.35 (1.55)	6.49 (0.44)	7.88 (0.97)	7.61 (0.59)
0.25-0.50	7.86 (0.55)	9.99 (0.28)	7.29 (1.00)	7.03 (0.89)
0.125-0.25	2.37 (0.19)	7.30 (1.06)	2.32 (0.23)	2.73 (0.25)
< 0.125	42.00 (1.04)	49.16 (0.74)	52.68 (1.35)	56.40 (3.43)

* mean of three replicates
Figures in brackets are standard deviation values

Table A6.1 Comparison between predicted and measured draught force at 42% moisture content (dry basis)

Treatment w x z x α	Measured values (N)	Predicted values (N)
25.4x50.8x45	142.25	72.31
50.8x50.8x45	214.50	145.45
25.4x101.6x45	327.79	203.88
50.8x101.6x45	400.50	292.91
25.4x152.4x45	500.36	343.70
50.8x152.4x45	772.15	551.05
25.4x50.8x90	214.50	156.84
50.8x50.8x90	286.34	332.27
25.4x101.6x90	376.05	305.32
50.8x101.6x90	679.98	629.24
25.4x152.4x90	555.09	454.57
50.8x152.4x90	879.96	927.73
25.4x50.8x135	316.12	268.44
50.8x50.8x135	512.14	483.97
25.4x101.6x135	637.81	675.90
50.8x101.6x135	1144.25	1074.40
25.4x152.4x135	1303.11	1233.30
50.8x152.4x135	1913.04	1815.05

Table A6.2 Comparison between predicted and measured draught force at 56% moisture content (dry basis)

Treatment w x z x α	Measured values (N)	Predicted values (N)
25.4x50.8x45	78.48	42.47
50.8x50.8x45	118.35	85.62
25.4x101.6x45	180.85	118.77
50.8x101.6x45	258.52	172.91
25.4x152.4x45	278.77	198.92
50.8x152.4x45	408.30	326.57
25.4x50.8x90	94.12	84.47
50.8x50.8x90	183.56	179.08
25.4x101.6x90	212.55	164.62
50.8x101.6x90	352.40	339.37
25.4x152.4x90	306.87	245.35
50.8x152.4x90	454.84	500.84
25.4x50.8x135	174.40	148.15
50.8x50.8x135	282.56	267.11
25.4x101.6x135	351.89	373.05
50.8x101.6x135	565.12	593.08
25.4x152.4x135	753.70	680.76
50.8x152.4x135	1145.82	1002.07

Table A6.3 Comparison between predicted and measured draught force at 70% moisture content (dry basis)

Treatment w x z x α	Measured values (N)	Predicted values (N)
25.4x50.8x45	29.43	17.15
50.8x50.8x45	44.38	34.93
101.6x50.8x45	62.34	72.41*
152.4x50.8x45	85.89	112.45*
25.4x101.6x45	67.82	46.93
50.8x101.6x45	101.47	74.64
101.6x101.6x45	142.38	147.90*
152.4x101.6x45	191.93	229.50*
25.4x152.4x45	118.24	77.35
50.8x152.4x45	150.94	135.47
25.4x50.8x90	40.22	32.32
50.8x50.8x90	64.46	68.72
101.6x50.8x90	126.41	139.97*
152.4x50.8x90	189.71	212.23*
25.4x101.6x90	81.75	63.29
50.8x101.6x90	138.95	130.66
101.6x101.6x90	188.50	279.21*
152.4x101.6x90	395.16	427.87*
25.4x152.4x90	125.64	94.83
50.8x152.4x90	220.88	193.74
25.4x50.8x135	65.40	55.62
50.8x50.8x135	105.96	100.33
101.6x50.8x135	222.43	203.44
152.4x50.8x135	292.12	324.89
25.4x101.6x135	164.66	140.16
50.8x101.6x135	252.07	222.97
101.6x101.6x135	403.64	402.37
152.4x101.6x135	577.80	600.21
25.4x152.4x135	298.42	255.87
50.8x152.4x135	429.20	376.99

* Predicted values using wide blade theory with crescent effect considered.

Table A6.4 Comparison between predicted and measured vertical force at 42% moisture content (dry basis)

Treatment w x z x α	Measured values (N)	Predicted values (N)
25.4x50.8x45	51.58	36.97
50.8x50.8x45	151.51	74.36
25.4x101.6x45	88.27	152.22
50.8x101.6x45	202.76	149.76
25.4x152.4x45	107.46	277.87
50.8x152.4x45	326.26	372.21
25.4x50.8x90	45.03	29.58
50.8x50.8x90	130.03	104.87
25.4x101.6x90	54.22	36.36
50.8x101.6x90	146.99	118.64
25.4x152.4x90	63.25	43.60
50.8x152.4x90	158.30	132.91
25.4x50.8x135	208.44	156.19
50.8x50.8x135	416.88	334.29
25.4x101.6x135	398.75	301.70
50.8x101.6x135	797.50	625.36
25.4x152.4x135	606.10	447.50
50.8x152.135	1212.20	916.98

Table A6.5 Comparison between predicted and measured vertical force at 56% moisture content (dry basis)

Treatment w x z x α	Measured values (N)	Predicted values (N)
25.4x50.8x45	27.78	18.70
50.8x50.8x45	68.40	37.68
25.4x101.6x45	45.93	77.28
50.8x101.6x45	119.75	76.07
25.4x152.4x45	47.93	140.02
50.8x152.4x45	183.61	193.51
25.4x50.8x90	29.80	23.51
50.8x50.8x90	53.16	72.58
25.4x101.6x90	32.39	34.42
50.8x101.6x90	65.56	94.41
25.4x152.4x90	36.27	45.58
50.8x152.4x90	87.46	116.72
25.4x50.8x135	115.00	86.21
50.8x50.8x135	236.00	184.53
25.4x101.6x135	230.00	166.60
50.8x101.6x135	465.00	345.34
25.4x152.4x135	346.15	247.21
50.8x152.4x135	692.28	506.59

Table A6.6 Comparison between predicted and measured vertical force at 70% moisture content (dry basis)

Treatment w x z x α	Measured values (N)	Predicted values (N)
25.4x50.8x45	15.53	8.78
50.8x50.8x45	32.40	17.86
101.6x50.8x45	54.55	36.91*
152.4x50.8x45	66.40	57.15*
25.4x101.6x45	30.66	33.61
50.8x101.6x45	53.82	40.81
101.6x101.6x45	100.58	75.25*
152.4x101.6x45	135.30	116.44*
25.4x152.4x45	62.08	58.81
50.8x152.4x45	121.93	91.21
25.4x50.8x90	9.81	8.11
50.8x50.8x90	14.95	26.77
101.6x50.8x90	50.32	56.83*
152.4x50.8x90	67.59	86.06*
25.4x101.6x90	17.77	11.08
50.8x101.6x90	33.28	32.71
101.6x101.6x90	63.38	106.97*
152.4x101.6x90	102.70	173.37*
25.4x152.4x90	18.54	14.26
50.8x152.4x90	56.16	39.06
25.4x50.8x135	43.13	32.40
50.8x50.8x135	90.00	69.36
101.6x50.8x135	180.00	156.99
152.4x50.8x135	270.00	262.96
25.4x101.6x135	86.25	62.74
50.8x101.6x135	172.50	130.06
101.6x101.6x135	345.00	278.50
152.4x101.6x135	517.50	445.37
25.4x152.4x135	135.44	93.29
50.8x152.4x135	258.75	191.18

* Predicted values using wide blade theory with crescent effect considered.

Table A6.7 Relationship between experimental and predicted horizontal and vertical force components.

a) Rake angle = 45^0.

Statistics	Horizontal			Vertical		
	Moisture content			Moisture content		
	42	56	70	42	56	70
r	0.993	0.983	0.850	0.36	0.35	0.95
b	0.75*	0.83*	1.14*	0.89NS	0.77NS	0.82*
95% UCL	0.77	0.87	1.24	1.26	1.09	0.86
95% LCL	0.75	0.79	1.04	0.52	0.45	0.78
a	-26.50*	-25.40*	-18.80*	39.00NS	27.30NS	-1.30NS
95% UCL	-16.36	-15.66	-11.61	104.88	59.15	-1.69
95% LCL	-36.64	-35.14	-25.90	-26.90	-4.55	-4.30

b) Rake angle = 90^0.

Statistics	Horizontal			Vertical		
	Moisture content			Moisture content		
	42	56	70	42	56	70
r	0.939	0.932	0.913	0.99	0.97	0.88
b	1.06NS	1.12*	1.13*	0.91*	1.59*	1.66*
95% UCL	1.15	1.23	1.20	0.92	1.69	1.79
95% LCL	0.96	1.01	1.06	0.89	1.48	1.53
a	-59.84*	-46.18*	-13.60*	-12.60*	-16.10*	-16.80*
95% UCL	-7.05	-14.97	-0.32	-11.26	-10.42	-10.12
95% LCL	-112.63	-77.39	-26.88	-13.86	-21.83	-23.48

c) Rake angle = 135^0.

Statistics	Horizontal			Vertical		
	Moisture content			Moisture content		
	42	56	70	42	56	70
r	0.995	0.979	0.971	0.997	0.998	0.980
b	0.95*	0.86*	1.03NS	0.76*	0.73*	0.88*
95% UCL	0.97	0.90	1.07	0.77	0.74	0.90
95% LCL	0.92	0.81	0.99	0.74	0.72	0.85
a	6.59NS	41.86*	-20.92NS	3.60NS	3.48NS	-12.10*
95% UCL	32.54	70.19	9.22	13.55	8.13	-5.60
95% LCL	-19.36	13.53	-32.61	-6.29	-1.18	-18.86

NS = Not significant at 95% confidence level from either a = 0.0 or b = 1.0.

* = Significant at 95% confidence level from either a = 0.0 or b = 1.0.

UCL = Upper confidence level.

LCL = Lower confidence level.

Appendix B.

A Computer Program to Calculate the Percentage Saturation Levels Within a Clod.

```
      INTEGER T,R
      DIMENSION THETAT(10,10)
      OPEN(1,FILE='OUT.DAT',STATUS='NEW',FORM='FORMATTED')
      D=4.36
      A=60.00
      PI=22/7
      V=100.00
      THETAT=76.26
      WRITE(6,40)
      DO 30 R=10,60,10
         Z=PI*R/A
         DO 20 T=1,7
            SUM=0.0
            DO 10 N=1,100
                X=-1*D*T*(N*PI/A)**2
              ANG=N*Z
                Y=SIN(ANG)*EXP(X)
                U=V*COS(PI*N-THETA)/N*SIN(N*Z)
10              Q=U*2/PI
                S=Y*2/A
              SUM=SUM+Q+S
         THETAT(R,T)=(V-THETA)*R/A+THETA+SUM
20    WRITE(6,50)R,T,THETAT(R,T)
30    CONTINUE
40    FORMAT(2X,'R',3X,'T',1X,'THETAT(R,T'/)
50    FORMAT(1X,I3,I4,1X,F7.2)
      STOP
      END
```

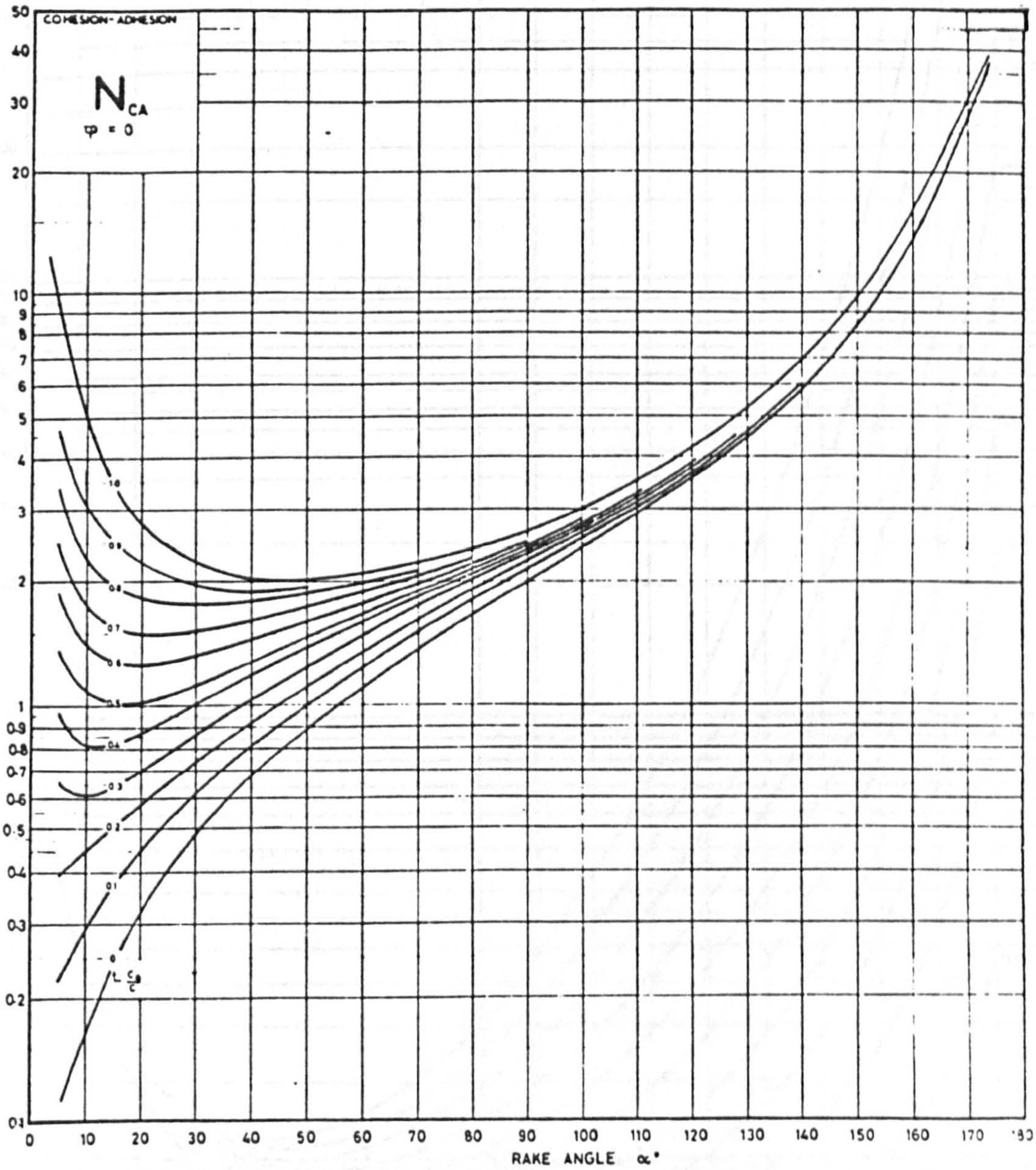
Appendix C.

A Computer Program to Calculate the Tine Forces and a Set of Charts to Determine the Soil Resistance Coefficients.

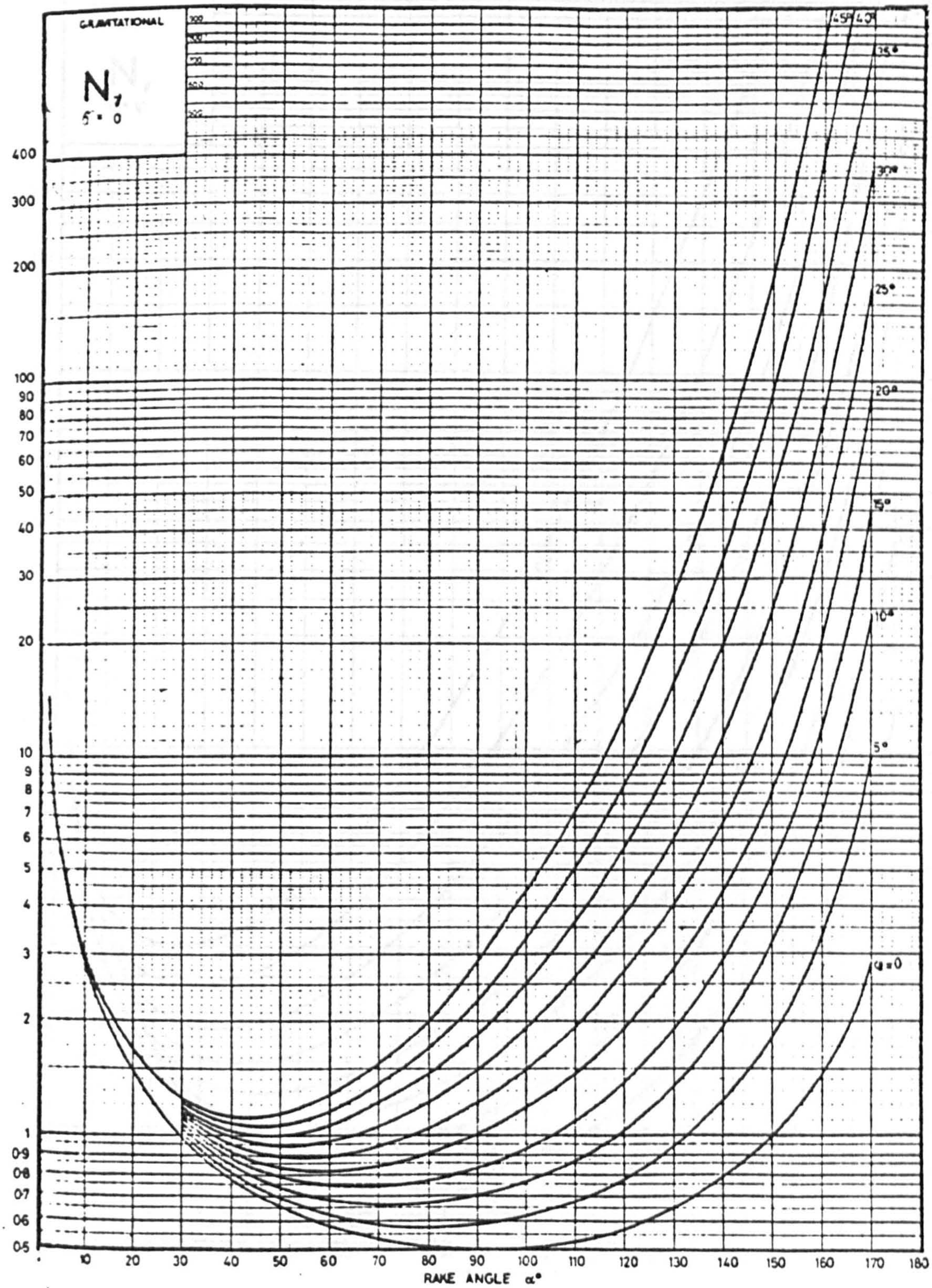
```
C     REAL NY, NCA, NC1, NQ1, MO, MM, NC2, NQ2
      PARAMETER(P=3.14156)
      PARAMETER(CO1=0.0254)

      OPEN(1,FILE='INPUT.DAT',STATUS='OLD',FORM='FORMATTED')
      OPEN(3,FILE='OUTPUT.DAT',STATUS='NEW',FORM='FORMATTED')

      WRITE(6,*)'ENTER VALUES FOR:Y,CA,C,DEL'
      READ(5,*)Y,CA,C,DEL
      DD=DEL*P/180

C WRITE OUTPUTS
C HEADINGS
      WRITE(3,400)
      WRITE(3,401)
      WRITE(3,402)
      WRITE(3,403)
400   FORMAT(////1X,'**********************************'/)
401   FORMAT(3X, 'CALCULATION OF FORCES ACTING ON'/)
402   FORMAT(3X, 'TINES AT DIFFERENT RAKE ANGLES.'/)
403   FORMAT(3X, 'PARAMETERS ARE AS FOLLOWS:'/)

      Y=Y*9.81

      DO 30 K=1,3
        READ(1,*) ALF, TB, FI
        READ(1,*) NY, NCA, NC1, NQ1, MO, NC2, NQ2

      WRITE(3,410)
410   FORMAT(1X,'****SOIL PARAMETERS:****'/)
      WRITE(3,411) ALF
      WRITE(3,412) MO
      WRITE(3,413) NY
      WRITE(3,414) NCA
      WRITE(3,415) NQ1
      WRITE(3,416) NC1
      WRITE(3,417) NQ2
      WRITE(3,418) NC2
411   FORMAT(1X, 'RAKE ANGLE, ALF= ',F8.3,' DEGREES'/)
412   FORMAT(1X, 'RUPTURE DISTANCE RATIO,MO= 'F6.3/)
413   FORMAT(1X, 'NY-FACTOR, NY= ',F6.3/)
414   FORMAT(1X, 'NCA-FACTOR,NCA= ',F6.3/)
415   FORMAT(1X, 'NQ-FACTOR1,NQ1= ',F6.3/)
416   FORMAT(1X, 'NC-FACTOR1,NC1= ',F6.3/)
417   FORMAT(1X, 'NQ-FACTOR2,NQ2= ',F6.3/)
418   FORMAT(1X, 'NC-FACTOR2,NC2= ',F6.3/)

      AA=ALF*P/180
      FF=FI*P/180
      P45=45.*P/180
      THETA=36.87*P/180
      AD=AA+DD

      DO 10 I=2, 6, 2
        Z=I*CO1
        DO 20 J=1, 7, 2
            W=(J-1.)*CO1
            IF (W.EQ.0) W=1.*CO1
```

```
C CHECK FOR THE RAKE ANGLE IN OPERATION;

      IF(ALF.EQ.135.) THEN
C CALCULATE THE FORCES ACTING ON TINES FOR 135 DEGREE RAKE ANGLE
      BB=Y*NQ1*(1.-SIN(FF))/2.
      CC=BB*NQ2
      H2=W*C*NC1*Z/2
       S=(SQRT(1.25*Z**")+W/2.)/2.
      SR=C*(Z**2+W*Z)
      BD=S*THETA
      H1=H2+BB*Z**2*W/4
      H3=(C*NC2*BD+CC*BD**2)*W
       H=H1+SR+H3*COS(P45)
       V=H1+H3*SIN(P45)
       A=0.
       ARC=0.

       ELSE

C CALCULATE THE FORCES ACTING ON TINES FOR 45 AND 90 DEGREE

  RAKE ANGLES

      A=Z/W
      MM=MO-(MO-1.)/3.
      W2=W**2
      W3=W**3
      PP=Y*W3*NY
      TT=W2*C
      TT1=TT*NC1
       SS=(1.-SIN(FF))*Y*W3*NQ1
       QQ=TT*NCA
       RR=W2*CA

       ADC=3.*PP*MM*SIN(AD)
       BDC=2.*PP+2.*QQ*MM+2.*W2*MO
       CDC=RR*COS(AA)/SIN(AA)-TT1-TT*COS(AA)/COS(P45)-SS*SIN(AD)
       BET=SQRT(BDC**"-4.*ADC*CDC

       ARC1=(-BDC+BET)/(2*ADC)
       ARC2=(-BDC-BET)/(2*ADC)

       IF(ARC1.LT.0.)ARC1=0.
       IF(ARC2.LT.0.)ARC2=0.

       ARC=AMAX1(ARC1,ARC2)
       IF(ARC.GT.A)B=A
       IF(ARC.LT.A)B=ARC

       B3=B**3
       B2=B**2
       PP1=PP*B2
       PP2=PP*B*MM
       QQ1=QQ*B
       RR1=B*MM
       RR2=B2*W2
       QQ2=QQ*RR1
       QQ3=TT*(A-B)
```

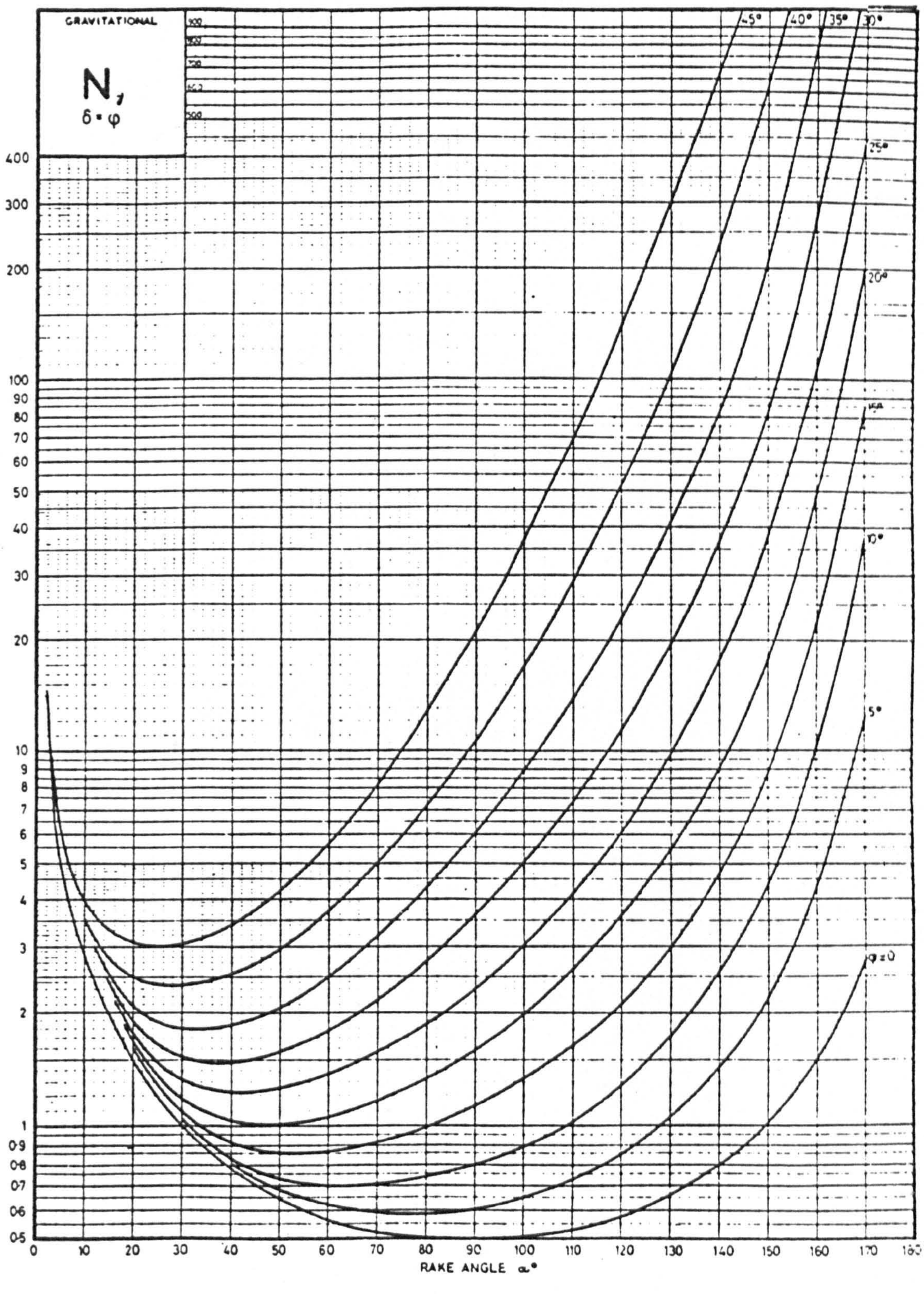
```
      QQ4=TT1*(A-B)
       AB=A**2-B2
      SS1=0.5*SS*AB
      SUB=PP1+PP2+QQ1+QQ2+RR2*MO

      IF(ARC.GT.A) THEN
        H=SUB*SIN(AD)+QQ5/TAN(AA)
        V=QQ5+TB*SUB*COS(AD)

      ELSE IF(ARC.LT.A) THEN
        SUB1=SUB-QQ3+QQ4+SS1
        SUB2=SUB+QQ4+SS1
           H=SUB1*SIN(AD)+QQ5/TAN(AA)
           V=QQ5+TB*QQ3*SIN(AA)/COS(P45)+TB*SUB2*COS(AD)

         END IF
      END IF

          WRITE(3,419) Z, W
          WRITE(3,420) ARC
          WRITE(3,421) A
          WRITE(3,422)
          WRITE(3,423) H
          WRITE(3,424) V
419       FORMAT(//1X,'DEPTH= ',F6.3,' WIDTH=',F6.3/)
420       FORMAT(1X,'CRITICAL ASPECT RATIO= ',F6.3)
421       FORMAT(1X,'ASPECT RATIO= ',F6.3/)
422       FORMAT(1X,'CALCULATED FORCES:- ')
423       FORMAT(1X,'DRAUGHT= ',F8.2)
424       FORMAT(1X,'VERTICAL FORCE= ',F8.2//)

20         CONTINUE
10        CONTINUE
30       CONTINUE

         STOP
         END
```



(Hettiaratchi et. al, 1966)



(Hettiaratchi et. al, 1966)



(Hettiaratchi et. al, 1966)